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Incidence of Compression Wood and Stem Eccentricity in Lodgepole Pine of North America

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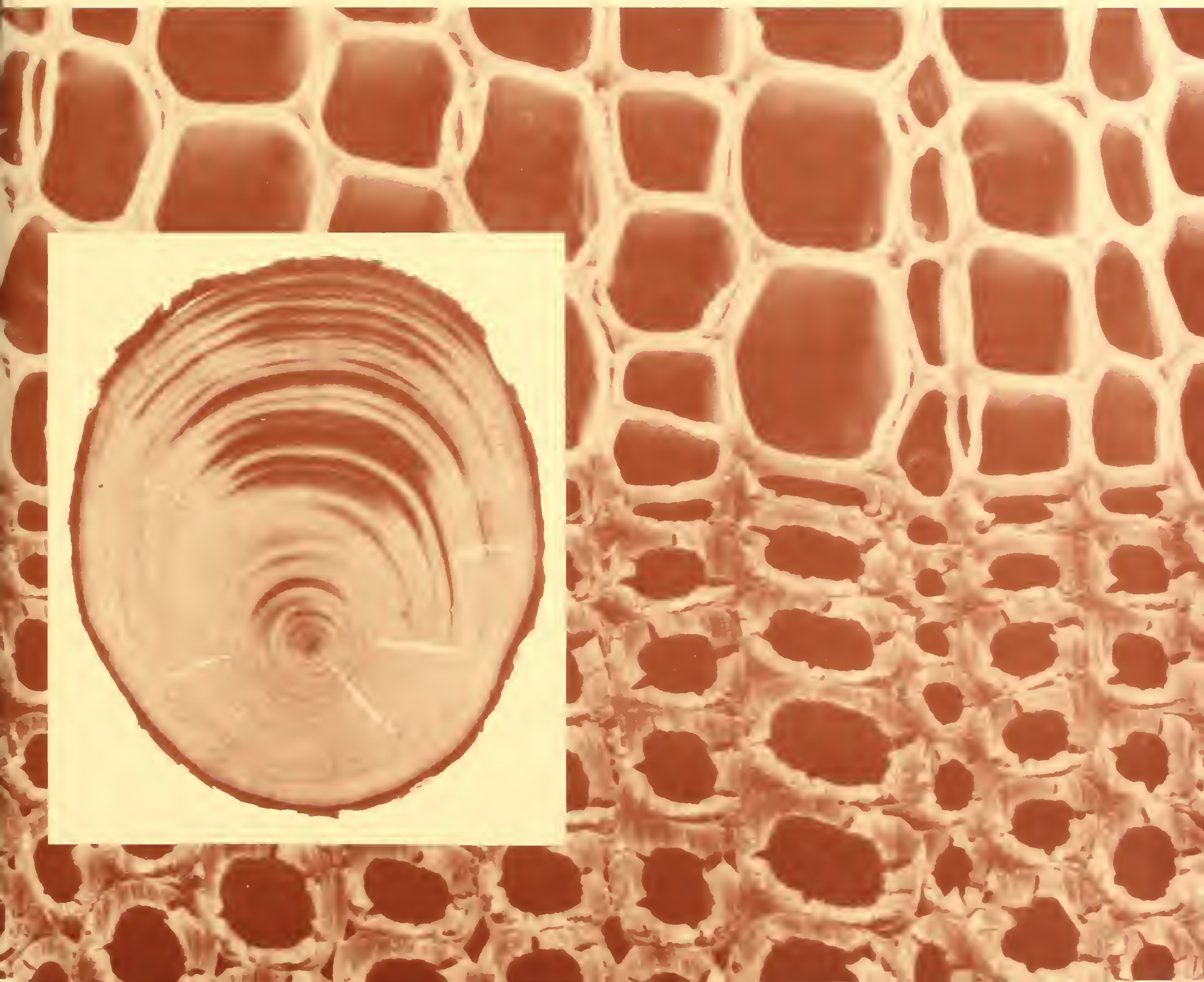

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ACKNOWLEDGMENTS

The substantial contribution of the Canadian Forestry Service, working through the University of British Columbia, during the tree-collection phase of the study is appreciatively acknowledged. Under the direction of Dr. Robert Kennedy, Dean of the Faculty of Forestry of UBC, 135 lodgepole pines in five latitudinal zones of Canada (see figure 1) were collected during the summers of 1983 and 1984—thereby extending the entire collection from near the southern limit of the species in the United States to near the northern limit in Canada and greatly enhancing the value of this and related characterization studies.

RESEARCH SUMMARY

Although present in virtually all lodgepole pines, compression wood is extremely difficult to detect visually in log ends in a woods or mill environment. Of 243 *latifolia* trees sampled from 40° to 60° latitude, only one was free of compression wood; none of the 36 *murrayana* trees sampled from 37.5° to 45° latitude were free of compression wood. Trees 76 mm in d.b.h. of both varieties had significantly higher stem-average percentage of compression wood than those 152 mm or 228 mm in d.b.h. *Latifolia* trees had less compression wood (5.5 percent) than *murrayana* trees (7.7 percent). In both varieties, sections sampled from 45° through 50° latitude had the greatest proportion of sections free of compression wood.

Transverse stem sections typically display a compression wood pattern of one-sided eccentricity in which the main body of compression wood is opposite an eccentrically located pith, and along a line projected from pith through the center of the largest circle that can be inscribed in the section. Sections or short logs sampled from stems of both varieties tend to have high percentages of compression wood if they are out of round and close to ground level, and have eccentric piths, high specific gravities, and low moisture contents.

Stemwood averages most elliptical in cross section in trees from 57.5° and 60° latitude. Stemwood of both varieties is most nearly circular in cross section near midheight of trees.

Tree-average pith eccentricity averages 6.7 mm and does not differ between varieties. In *latifolia* it is smallest (5.5-6.3 mm) in the intermediate latitudinal zone from 45° to 52.5°, and is larger in more southerly and more northerly latitudes (6.8-8.0 mm).

RELATED PUBLICATIONS

Readers interested in further studying characteristics of lodgepole pine in North America related to its utilization should find useful the following books and papers tabulated by date of publication—each part of a series on the subject (see References for complete citations):

Citation	Subject
Burke (1985)	Anatomical variations of lodgepole pine in North America (study in progress)
Koch (1987a)	Gross characteristics of lodgepole pine in North America
Koch (1987b)	Spiral gram in stemwood of lodgepole pine in North America (study in progress)
Koch and Barger (1988)	Atlas of 28 selected commercial forest areas in the United States with unutilized stands of lodgepole pine
Koch and others (1989)	Proposed wood products plant to utilize sub-sawlog-size and dead lodgepole pine in northwestern Montana—a technical and economic feasibility analysis
Kim and others (1989)	Chemical variation in lodgepole pine with latitude, elevation, and diameter class
Kossuth and Koch (1989)	Stimulation of oleoresin flow in lodgepole pine lower stem and rootwood
Pellerin and others (1989)	Mechanical properties of lodgepole pine: 3-inch diameter stems
Pellerin and others (1989)	Mechanical properties of lodgepole pine: 6- and 9-inch diameter stems
Campbell and others (1990)	Chemical variation in lodgepole pine with sapwood/heartwood, stem height, and variety (includes ultimate and proximate analyses)
Wiedenbeck and others (in press)	Air permeability, shrinkage, and moisture sorption of lodgepole pine

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PROBLEMS INDUCED BY COMPRESSION WOOD

Timell (1986, p. 579) has succinctly summarized the problems related to utilization of compression wood:

> From a wood utilization point of view, compression wood has many drawbacks. Most serious is its high longitudinal shrinkage which causes warping and other distortions in lumber containing both normal and compression woods. Its second most serious disadvantage is its low ability to increase in strength on drying, which renders it weaker than normal wood not only in tension, which it is under all circumstances, but also in many properties related to compression and bending. A third drawback is the brash rupture characteristic of compression wood which, where it occurs in construction lumber, can render a danger to life and property. As a fourth disadvantage must be listed the great hardness of compression wood, which makes it difficult, if not impossible, to nail or work with ordinary tools.

While not emphasized by Timell in the above passage, modulus of elasticity—a critical property of structural wood—is very much less for compression wood than for normal wood. Since stiffness of structural wood members more frequently controls design than ultimate load, this deficiency is a serious shortcoming in compression wood. Also, compression wood has less alpha cellulose and more lignin than normal wood, characteristics adversely affecting its utility as pulpwood.

The problem faced by North American manufacturers of lodgepole pine products is that the literature affords no assessment (locally or rangewide) of the incidence of compression wood in the stemwood of the species, and hence manufacturers have no rationale for avoiding stems with excessive compression wood content; neither do they have a clear picture of its pervasiveness.

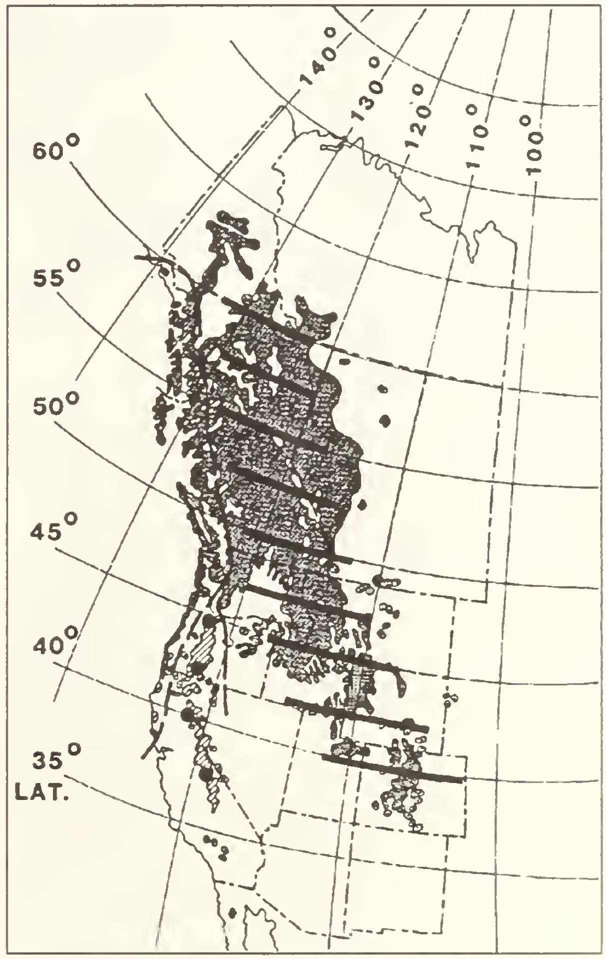


Figure 1—Sampling zones superimposed on Little's (1971) range map of lodgepole pine in North America. Variety *latifolia* is mapped to the right of the dashed lines, *murrayana* between them, and *contorta* to the left of them. Variety *contorta* was not studied because of its small potential for commercial use.

STUDY SCOPE AND OBJECTIVES

The purpose of this study was to ascertain the incidence of compression wood in the stemwood of the two principal varieties of lodgepole pine (*Pinus contorta* var. *latifolia* Engelm. and *Pinus contorta* var. *murrayana* [Grev. and Balf.] Engelm.) throughout their major ranges in North America (fig. 1), and to correlate this incidence with height in tree, degree of pith eccentricity, and stem out-of-roundness—and with other selected variables such as latitude, longitude, elevational zone, diameter at breast height (d.b.h.), tree height, magnitude of stem crook, stemwood specific gravity, average growth ring width at stump height, crown ratio, number of branches, average

branch diameter, stem taper, length of tap root, and proportions of complete-tree weight represented by roots, bark, stemwood, branchwood, and foliage.

The primary objective during tree collection was to obtain disease-free and insect-free specimens of 76-, 152-, and 228-mm (3-, 6-, and 9-inch) lodgepole pine (var. *latifolia*) at low, medium, and high elevations from nine equally spaced north latitudinal zones (40 to 60 degrees) across 10 degrees of longitude, in such a way as to encompass the major range of this variety (fig. 1).

A secondary objective during tree collection was to sample these same three diameter classes of var. *murrayana* at midelevation at four north latitudes (37½, 40, 42½, and 45 degrees) in California and southern Oregon at a single longitude per latitude (fig. 1).

The trees of both varieties were sampled in such a way that between-variety comparisons could be made for midelevation trees from latitudes 40, 42½, and 45 degrees. The collection totaled 243 *latifolia* trees and 36 *murrayana* trees.

See table 1 for summary information on these trees.

Table 1—Summary information descriptive of the 279 lodgepole pines in the study. Data averaged over full range of sample, by variety

Variable	Tree diameter at breast height		
	76 mm	152 mm	228 mm
***Latifolia* (81 trees of each diameter)**			
Age at 152-mm-high stump top, years	71	91	107
Height from 152-mm-high stump top to apical tip, meters	9.3	15.6	19.1
Taproot length measured from 152-mm-high stump top, centimeters	55	78	94
Average width of annual rings at 152-mm-high stump top, millimeters	0.7	1.0	1.3
Average diameter outside bark of live branches 50 mm from stem, millimeters	9	13	19
Average branch angle, degrees[1]	85	79	77
Ratio of live-crown length to tree height (crown ratio)	0.48	0.44	0.45
Number of live branches	64	108	133
Number of dead branches	57	100	119
Stem taper inside bark below live crown, millimeters per meter	6.3	7.8	10.5
Stem taper inside bark from base of live crown to apical tip, millimeters per meter	13.1	15.9	18.5
Stemwood-average moisture content, percent	99	100	98
Stemwood-average specific gravity[2]	0.43	0.42	0.41
***Murrayana* (12 trees of each diameter)**			
Age at 152-mm-high stump top, years	67	84	91
Height from 152-mm-high stump top to apical tip, meters	7.4	13.7	18.7
Taproot length measured from 152-mm-high stump top, centimeters	58	91	97
Average width of annual rings at 152-mm-high stump top, millimeters	0.7	1.1	1.6
Average diameter outside bark of live branches 50-mm from stem, millimeters	7	12	18
Average branch angle, degrees[1]	88	83	78
Ratio of live-crown length to tree height (crown ratio)	0.60	0.55	0.59
Number of live branches	72	127	146
Number of dead branches	34	79	94
Stem taper inside bark below live crown, millimeters per meter	5.8	10.8	11.9
Stem taper inside bark from base of live crown to apical tip, millimeters per meter	14.5	16.0	16.6
Stemwood-average moisture content, percent	98	114	121
Stemwood-average specific gravity[2]	0.48	0.44	0.41

[1]Angle between branch and stem; upward-pointing branches less than 90°; drooping branches more than 90°.
[2]Based on green volume and ovendry weight.

LIMITATIONS OF THE STUDY

A work of this scope, describing trees of a species with great latitudinal, longitudinal, and elevational range, cannot meet the needs of readers of all disciplines. Recognizing this reality, the work was written principally for use by industrialists, scientists, process engineers, and students who need a description of gross species characteristics and some appreciation of their variation within North America.

Because the sampling plan calls for a specimen collection stratified by d.b.h., latitude, and elevational zone—without sampling intensity adjusted for volume distribution within these stratifications—it does not permit computation of species-average values valid rangewide. Moreover, the sampling plan does not permit evaluation of effects of site quality, age, and stand density—even though it is well known that these three parameters significantly affect many, perhaps most, of the characteristics evaluated. This shortcoming in experimental design was thoroughly discussed before study initiation.

As resources available for this study of lodgepole pine as an industrial raw material were not only finite, but modest, the study objectives were limited to determination of broad material-characteristics variations related to tree d.b.h. and spatial location (latitude, longitude, and elevational zone). The study was not designed to deal with the very complex relationships involving site quality, tree age, or stand density; as a result, the sampling plan does not permit such analyses.

The elevational range of lodgepole pine (*latifolia*) is considerably greater in southern latitudes than in northern (fig. 2); and it is probable that site quality and stand densities vary less in northern than in southern latitudes.

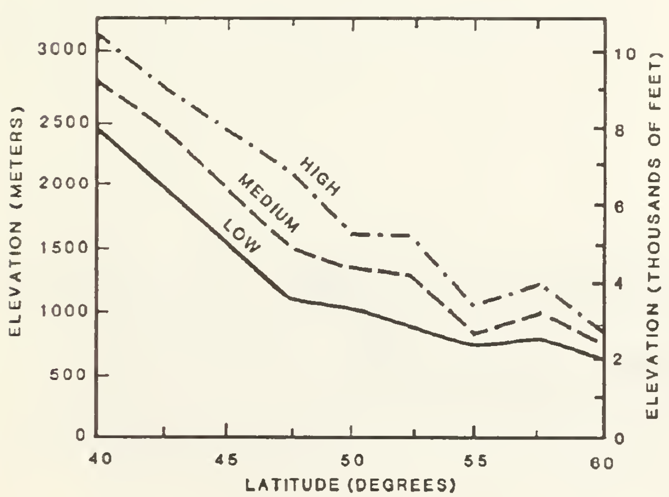


Figure 2—Elevational trends in the three zones (low, medium, and high) where lodgepole pine (var. *latifolia*) was sampled along nine latitudes. Each plotted point is the average for nine trees; that is, three diameters by three replications.

THE LODGEPOLE PINE RESOURCE IN NORTH AMERICA

To appreciate the scope of the work and to understand the rationale for the sampling design, it is useful to know something about the resource.

Lodgepole pine (*Pinus contorta* Doug. ex Loud.) occupies about $5^{1}/_{4}$ million ha of commercial forest land in the United States (containing 748 million m^3 of lodgepole growing stock and over 71 billion board feet of lodgepole timber, mostly in Montana, Idaho, Wyoming, Colorado, and Oregon), and is the fourth most extensive timber type west of the Mississippi River. On these $5^{1}/_{4}$ million ha, a significant proportion of the trees are dead, having been killed by insects. In the Northern Region alone, a 1979 survey reported 540,862 ha severely infested with mountain pine beetle. The most recent survey data for Idaho indicate that insects and disease have killed about 1 percent of the lodgepole pine trees. In Canada the acreage of lodgepole pine forest type (20 million ha, comprising 22 percent of the total forest land in western Canada) is greater than in the United States.

Most of the North American lodgepole pine resource is of the variety *latifolia* (*Pinus contorta* var. *latifolia* Engelm.) centered along the Rocky Mountains from 40 to 60 degrees north latitude, with Sierra lodgepole pine (*Pinus contorta* var. *murrayana* [Grev. & Balf.] Engelm. and shore pine (*Pinus contorta* Dougl. ex Loud. var. *contorta*) comprising significantly lesser volumes on Sierra and coastal areas (fig. 1). A fourth variety, *bolanderi* (Parl.) Vasey, is a shrub local in Mendocino County, CA.

In both Canada and the United States, much of the lodgepole resource is in older (60-200 years) virtually stagnated stands in which growth rate is very low and mortality very high. Typically trees are small in diameter. Slightly more than one-third of the volume (ovendry weight basis) is in trees less than 175 mm in diameter measured at breast height outside bark (Van Hooser and Chojnacky 1983); such a diameter might be considered the lower limit for lumber manufacture.

Silvicultural treatments (thinning or removal and regeneration to managed stand with controlled stocking) are so expensive, and stumpage revenue so little, much of the acreage has received no treatment to accelerate growth and slow mortality.

PAST AND CURRENT WORK

Timell's (1986) three-volume work on compression wood in gymnosperms is an up-to-date and thorough review of world literature on the subject. This section presents brief abstracts of some of Timell's conclusions regarding the physiology of compression wood formation, anatomical characteristics, chemical composition, knots and compression wood, and the mechanism of compression wood in righting a leaning tree. Also included are some additional data specific to lodgepole pine.

Timell notes that while trees with a high incidence of sweep, crook, lean, and fork contain more compression wood than straight stems, there apparently is no quantitative relationship between the amount and type of compression wood and the degree of stem displacement or

curvature. Most present-day investigators favor gravitational stimulus as the factor most probably involved in compression wood formation. Timell concludes that there is evidence of inheritance of a tendency to form compression wood per se, and that evidence for the inheritance of stem form and straightness, which are associated with the incidence of compression wood, is very strong.

Koch (1972, pp. 125-128) summarized, and illustrated with micrographs, essential features of compression wood in southern pines, which like lodgepole pine are hard pines—diploxylon members of the genus *Pinus*.

The literature contains a few papers specific to lodgepole pine—most of them stemming from work on plantations of the species introduced to England, Scotland, Ireland, and the Scandinavian countries. Comments on those most germane follow, along with some general comments on the anatomical and chemical characteristics of compression wood.

Physiology

Savidge (1983a, b) found that when vertical seedlings of lodgepole pine were brought in from the outdoors in late winter and placed in a darkened growth chamber, compression wood developed around the stem. In the same work, he reported that when indoleacetic acid was applied to a lodgepole pine shoot, compression wood developed immediately below the application site.

Timell (1986, p. 1247) concluded that the role of growth substances in the formation of compression wood is obscure though they do play some yet unexplained role in combination with gravistimulus; he further noted that it is highly uncertain, not to say improbable, that compression wood should be produced in mature trees as a consequence of redistribution of indoleacetic acid. A supraoptimal concentration of auxin, however, causes formation of compression wood. Among the auxins, idoleacetic acid, naphthalineacetic acid, and 2,4-dichlorophenoxyacetic acid are all known to induce compression wood formation when present in high enough concentrations.

See also the discussion of the mechanism of compression wood in righting a tree, under the heading "Stem Form and Compression Wood" in this section.

Anatomical Characteristics of Compression Wood

To understand the anatomical structure of compression wood in lodgepole pine, it is first useful to visualize the structure of normal wood in pines.

A wedge transversely cut from a lodgepole pine stem illustrates some of the features visible with the naked eye (fig. 3). The dark-colored **pith** is the small central core of parenchymatous tissue originating at the growing tip of the tree. On the periphery of the tree, wood is formed on one side and bark on the other side of the cambial layer. In a limb-free stem of lodgepole pine 76 to 228 mm in d.b.h., 85 to 91 percent of the volume is wood and 9 to 15 percent is bark—the proportion of bark being inverse to the d.b.h., so that small-diameter stems have a larger proportion of bark than large-diameter stems (Koch 1987, pp. 46 and 59).

Growth rings in lodgepole pine normal wood usually show an abrupt transition between the light-colored, thin-walled **earlywood** cells (fig. 4, 3-3a) formed early in the growing season, and the darker, thicker walled **latewood** (fig. 4, 4-4a) cells. (See figure 10 in the "Results" section for micrographs of transition from earlywood to latewood in normal and compression wood.) Total width of annual growth rings varies greatly in lodgepole pine, from barely visible with a hand lens to 4 or 5 mm (table 1). For all of the lodgepole pine trees in this study, growth ring width at 152-mm stump height averaged 1.00 mm for *latifolia* and 1.13 mm for *murrayana* (Koch 1987, pp. 20 and 53).

Heartwood (fig. 3) is darker than sapwood, contains no living cells, and because of resinous inclusions is less permeable and has less moisture content than sapwood. Heartwood volume in the lodgepole pine trees in this study, as a percentage of entire stemwood volume, was positively correlated with d.b.h., as follows (Koch 1987, pp. 273 and 299):

D.b.h.	***Latifolia***	***Murrayana***
mm	*- - - - - - - - Percent - - - - - - - -*	
76	22.0	10.3
152	28.3	16.9
228	34.2	20.3

The tissues and cell types observable by light microscopy in a block of southern pine wood are shown in figure 4; the cellular structure of lodgepole pine is very similar to that of southern pine (except that lodgepole pine lacks the longitudinal parenchyma, thick-walled parenchyma, spiral and callitroid-like thickenings, and pits on tangential walls of tracheids illustrated in figure 4). Pine wood consists principally of closely packed vertical cells, called **longitudinal tracheids**. Associated are horizontal tissues called **rays**, extending radially toward the pith, and specialized tissues surrounding vertical ducts called **resin canals**. Tracheids and other cells are interconnected through openings in the cell walls called **pits**, in most of which characteristic borders form **pit chambers**.

Cell walls are composed of elements too small to be visible through the light microscope, which is limited to about 0.2 micrometer (a micrometer is 10^{-3} mm). Electron microscopy, resolving to about 10 Angstrom (an Angstrom unit is 10^{-4} micrometers), reveals strands of **microfibrils**, some 100 to 300 Angstroms in diameter and of indefinite length, comprising the cellulose framework of the cell wall. These are in turn comprised of **elementary fibrils**, which presumably are cellulosic strands of the smallest possible cross-section—measuring about 35 Angstroms in diameter. An elementary fibril in turn consists of cellulose chains.

All of the horizontal elements in pine wood are contained in the rays (fig. 4)—ray tracheids, ray parenchyma, and epithelial cells.

Longitudinal elements of lodgepole pine wood are longitudinal tracheids, strand tracheids, and epithelial cells (fig. 4).

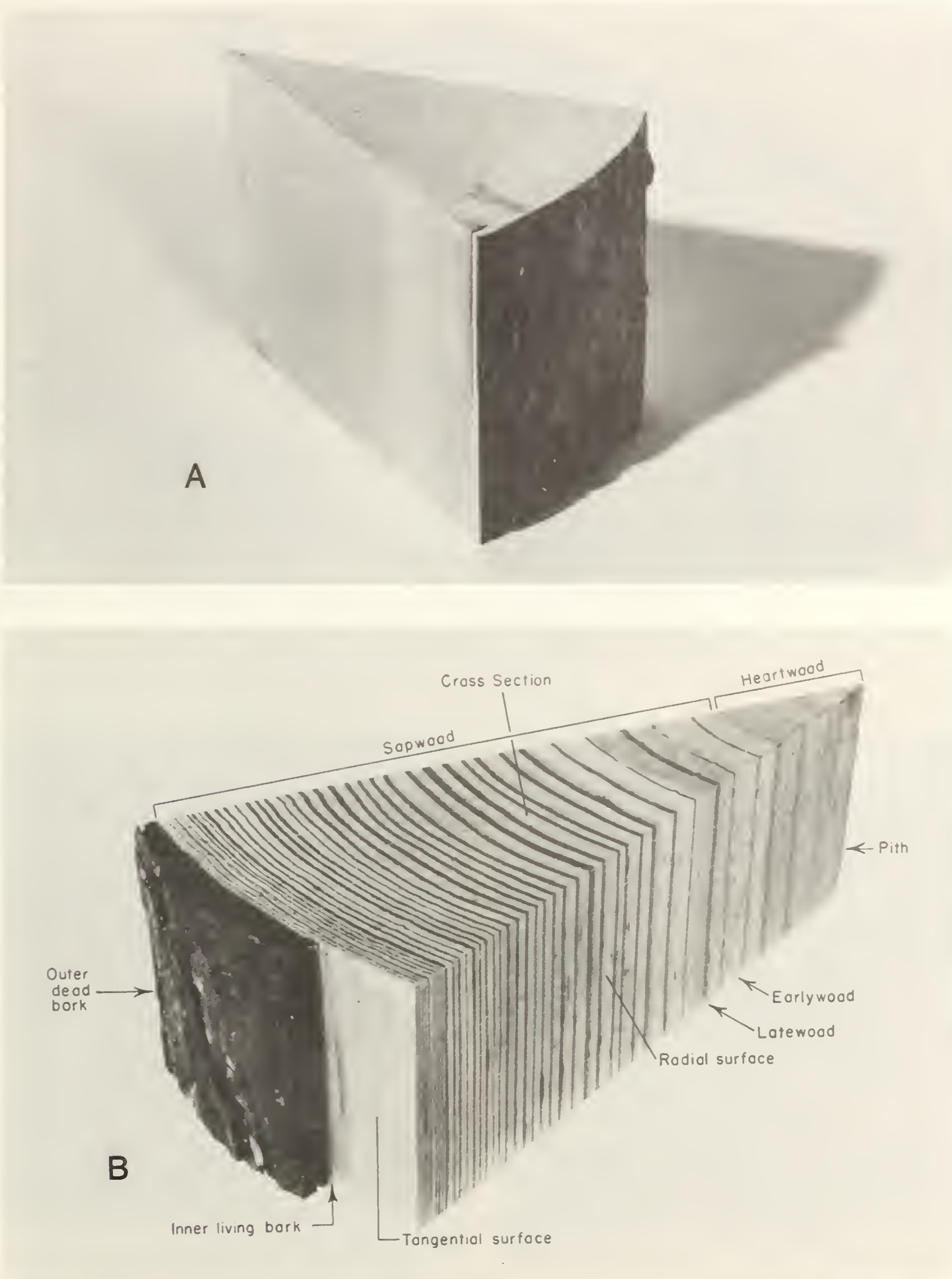


Figure 3—Gross anatomical features of stem sections from lodgepole and southern pines. (A) Typical narrow-ringed, thin-barked lodgepole pine with significant percentage of heartwood. The disk from which the wedge was cut measured about 90 mm in radius. (B) Typical fast-grown southern pine with thicker bark, wider rings, and more contrast between earlywood and latewood than lodgepole pine—and lesser percentage of heartwood in stems of comparable diameter.

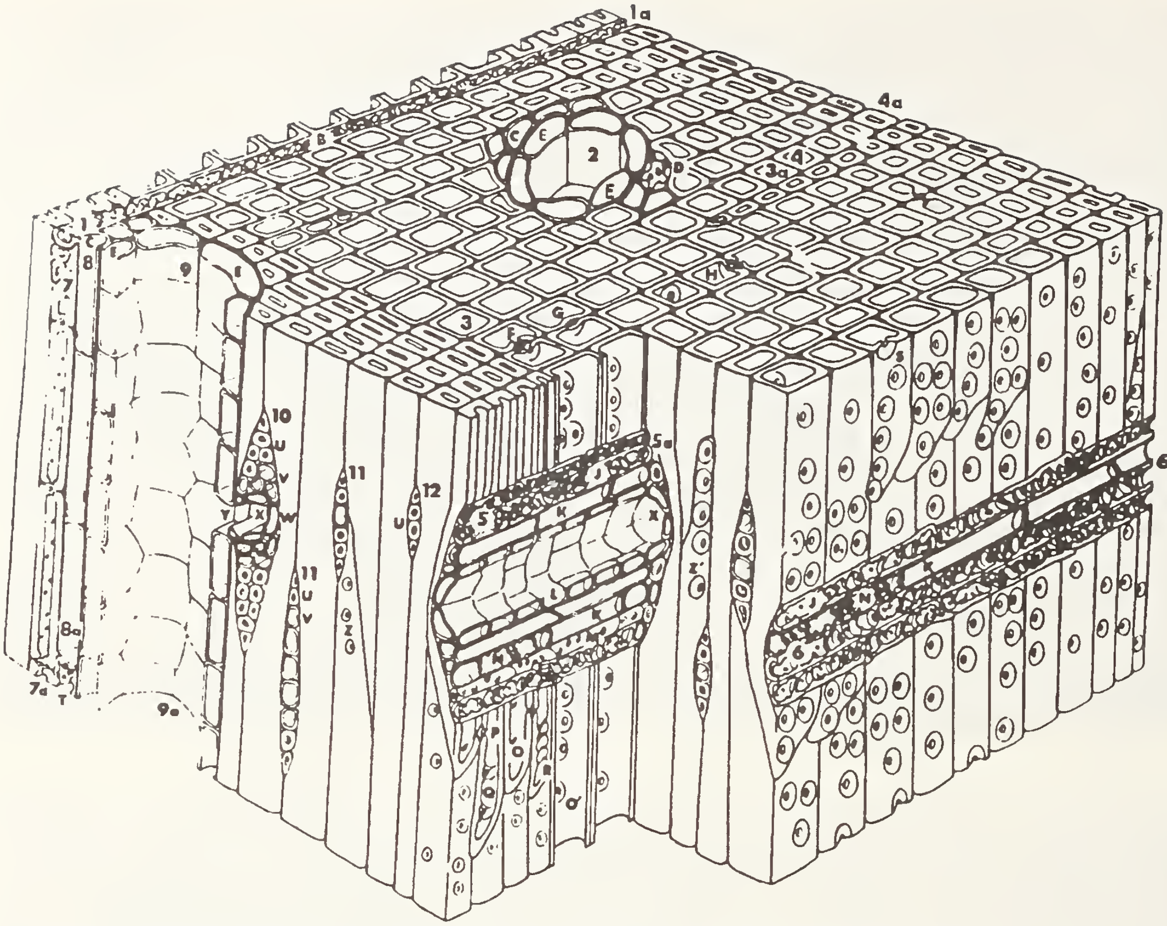


Figure 4—Typical southern pine wood. *Transverse view.* 1-1a, ray; B, dentate ray tracheid; 2, resin canal; C, thin-walled longitudinal parenchyma; D, thick-walled longitudinal parenchyma; E, epithelial cells; 3-3a, earlywood longitudinal tracheids; F, radial bordered pit pair cut through torus and pit apertures; G, pit pair cut below pit apertures; H, tangential pit pair; 4-4a, latewood longitudinal tracheids. *Radial view.* 5-5a, sectioned fusiform ray; J, dentate ray tracheid; K, thin-walled parenchyma; L, epithelial cells; M, unsectioned ray tracheid; N, thick-walled parenchyma; O, latewood radial pit (inner aperture); O', earlywood radial pit (inner aperture); P, tangential bordered pit; Q, callitroid-like thickenings; R, spiral thickening; S, radial bordered pits (the compound middle lamella has been stripped away, removing crassulae and tori); 6-6a, sectioned uniseriate heterogeneous ray. *Tangential view.* 7-7a, strand tracheids; 8-8a, longitudinal parenchyma, thin-walled; T, thick-walled parenchyma; 9-9a, longitudinal resin canal; 10, fusiform ray; U, ray tracheids; V, ray parenchyma; W, horizontal epithelial cells; X, horizontal resin canal; Y, opening between horizontal and vertical resin canals; 11, uniseriate heterogeneous rays; 12, uniseriate homogeneous ray; Z', small tangential pits in latewood; Z', large tangential pits in earlywood. (Drawing from Howard and Manwiller 1969.)

Because longitudinal tracheids make up more than 90 percent of the volume of pine wood, and because the differences between normal and compression wood in the structure of these cells account for the differences in their properties, further discussion is limited to longitudinal tracheids. For a fuller discussion of the anatomy of pine wood see Koch (1972).

Our intensive study of fiber length in lodgepole pine is incomplete, but existing literature indicates that longitudinal tracheids in mature lodgepole pine (var. *latifolia*) are $2\frac{1}{4}$ to $3\frac{3}{4}$ mm long, with average tangential diameter of about 27 microns. They are aligned radially as viewed in cross section (fig. 4) and have overlapping tapered ends.

The cell wall of the mature tracheid consists of an outer **primary wall** and a **secondary wall** (fig. 5a). Outside the primary wall is an **intercellular layer,** or **middle lamella,** composed largely of lignin. In the **secondary wall,** three layers are recognized; they are designated S_1 (outer), S_2 (middle), and S_3 (inner).

Tracheids of many of the hard pines, including the southern pines, have a warty layer lining tracheid lumens. Lodgepole pine tracheids appear to lack this feature; their interior walls are smooth (fig. 5b, left). Warty deposits were observed, however, within the bordered pit chambers of lodgepole pine (fig. 5b, right)—a feature typical of many species of the genus *Pinus*.

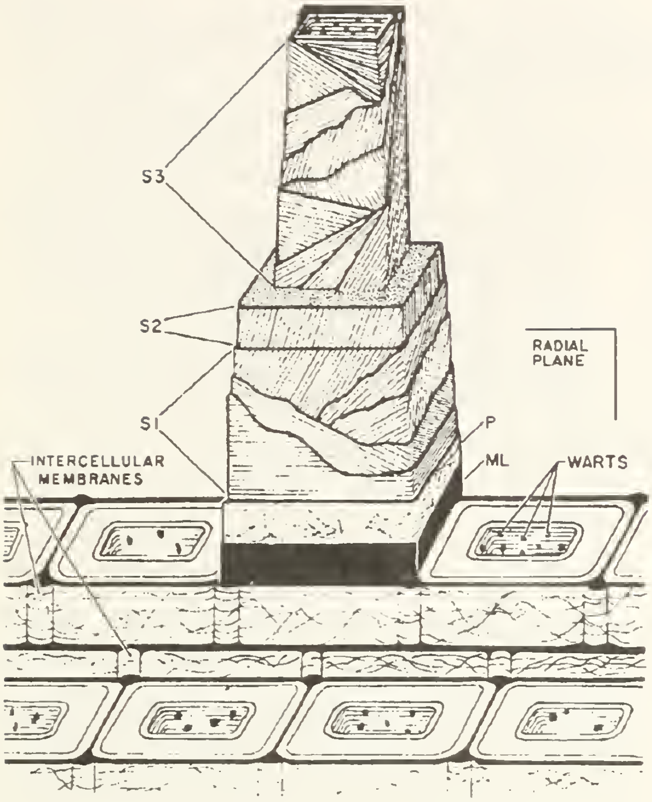
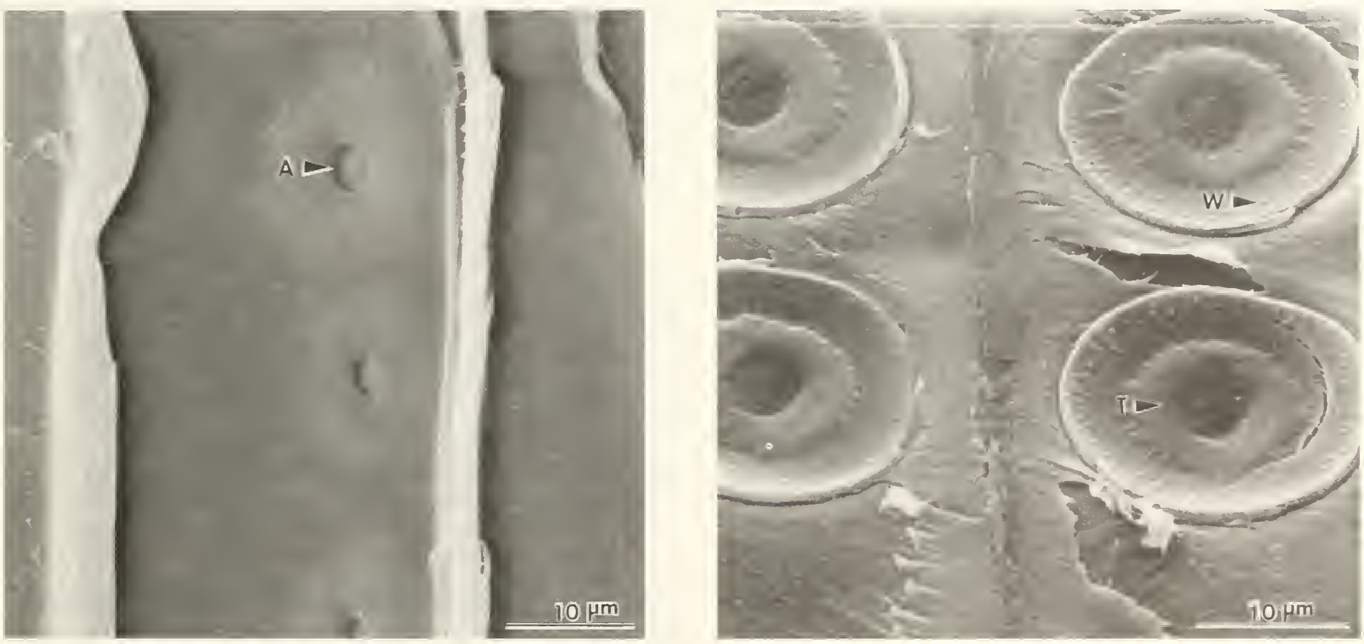


Figure 5a—Cell-wall structure of longleaf pine. A latewood longitudinal tracheid is exposed to show lamellae of the three layers of the secondary cell wall. Lines indicate alignment of microfibrils. ML is middle lamella. P is primary wall. S_1, S_2, and S_3 are layers of the secondary wall. (Drawing after Dunning 1969.) Lodgepole pine lacks the warty layer shown here (see fig. 5b). Also, lodgepole pine may have fewer lamellae in the S_1 and S_3 layers, and the S_2 may have several lamellae.



A

B

Figure 5b—Scanning electron micrograph of normal lodgepole pine wood. (A) Tracheid lumen walls with apertures of bordered pits; no warts visible. (B) Tracheid walls split longitudinally to expose, in radial aspect, portions of tracheids each with aspirated bordered pits and a coating of warts on pit chamber walls. W = warts; T = pit torus; A = pit aperture.

Three structural substances comprise the walls of wood cells. The framework is cellulose in the form of microfibrils. The matrix substances are hemicelluloses. Lignin occurs in intercellular layers and with the matrix materials surrounding the microfibrils; it may also be a component of the warty layers and the incrustation in cell interiors.

The outer envelope of longitudinal tracheids is the primary wall—a thin layer in which the cellulose microfibrils are randomly distributed. These fine strands are readily resolved with the electron microscope after some of the matrix substances have been removed (fig. 5a). Matrix polysaccharides, especially hemicelluloses, and pectin and lignin are the dominant components of primary walls.

In secondary cell walls, the framework of cellulose microfibrils is dominant. As previously noted, the secondary wall is comprised of three layers (fig. 5a): the outermost S_1, with multiple lamellae of microfibrils having varying alignments; the much thicker S_2 layer, which in normal wood has its microfibrils aligned most nearly with the longitudinal axis of the tracheid; and the thinner S_3 layer having multiple lamellae of varying alignments.

Fibril angle, the average angle between microfibrils in the S_2 layer and the tracheid longitudinal axis (fig. 6), is believed to be positively correlated with longitudinal shrinkage in wood.

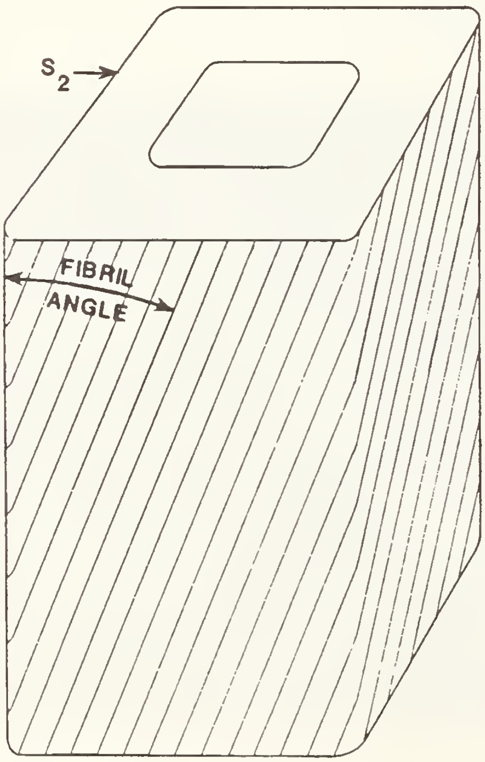


Figure 6—Fibril angle in the S_2 layer of the cell wall.

Longitudinal tracheids in compression wood differ from those of normal wood in a number of important ways that can be observed in transverse sections, as follows:

- Compression wood tissues show gradual transition from thin-walled earlywood cells to thick-walled latewood cells. (See figure 10 in "Results" section.)
- Tracheids in compression wood are distinguished by roundness of cells, by checks or cavities in the inner portion of the secondary wall, and by intercellular spaces. (See figure 11a in "Results" section.)
- With a polarizing microscope, it can be observed that the S_3 layer is missing from compression-wood tracheids. (See figure 11b in the "Results" section.)

Electron micrographs show that microfibrils in the S_2 layer of compression-wood tracheids make an abnormally large angle—sometimes more than 45°—with the longitudinal axis of the cell. This large angle, together with a higher lignin content than normal wood, impedes passage of light through cross sections of compression wood. In thin sections viewed over a light table, therefore, compression wood is readily discernible by its darker shades when compared to normal wood.

On a light table normal sapwood of lodgepole pine has a clear amber color; compression wood appears orange, to brown, to black depending on its severity. Depending on the presence of some or all of the attributes of compression wood discernible in cross section, that is:

- light impedence on a light table,
- gradual transition from thin-walled earlywood cells to thick-walled latewood cells (some authorities believe that the terms earlywood and latewood have little meaning when applied to compression wood),
- roundness of cells,
- presence of intercellular spaces,
- checks in the inner portion of the secondary wall,
- absence of S_3 layer,

the tissue under analysis can be classed as containing mild, moderate, or pronounced compression wood.

In this study, compression wood delineation was primarily accomplished by outlining areas with impeded light transmission. Scanning electron microscopy validations were periodically made on questionable areas. Researchers who have used this method of compression wood delineation will agree that such delineation can only be approximate.

Chemical Constituents of Compression Wood

A thorough review of the chemistry of compression wood is beyond the scope of this paper, but can be found in Timell (1986, pp. 289-468). Because of the significance of both cellulose content and lignin content to the pulp industry, however, it is useful to have some idea of the chemical constituents of both normal wood and compression wood of lodgepole pine.

Table 2—The average and range of pH and chemical composition of *latifolia* and *murrayana* trees with latitude, elevation, and tree diameter data pooled.[1,2] Data from Kim and others (1989)

Item	*Latifolia*		*Murrayana*	
	Average	Plus or minus	Average	Plus or minus
pH	4.57	(0.10)	4.64	(0.12)
Ash, percent	.26	(.05)	.28	(.06)
Extractives, percent	2.87	(.98)	2.41	(.67)
Lignin, percent	25.81	(.98)	26.40	(1.58)
Holocellulose, percent	80.40	(2.47)	83.26	(2.20)
Alpha cellulose, percent	49.64	(2.54)	51.83	(2.54)

[1]Each value is a mean from the 243 *latifolia* or 36 *murrayana* trees.

[2]The moisture (ASTM D 2016-74), ash (ASTM D 1102-56), ethanol-toluene extractives (ASTM D 1107-56), lignin (ASTM D 1106-56), and alpha cellulose (ASTM D 1103-60) content were measured following standard procedures. Toluene was substituted for benzine in the extractive analysis (Goetzler 1982). The pH and chlorite holocellulose contents were measured using the Forest Products Laboratory Methods 67-033 and 67-018, respectively. The average chemical composition was calculated on an ovendry wood basis.

Stemwood-average analyses of var. *latifolia* and var. *murrayana* performed on the same 279 lodgepole pine trees that were used in the current study of compression wood yielded mean values of near 50 percent for alpha cellulose and about 26 percent for lignin (table 2). The specimens for these analyses were taken at tenth points in height up each tree, in a manner similar to that used in sampling for the compression wood study here reported. Because any compression wood present in the stem was included in the chemical-analysis samples, the overall analyses probably indicate a lower cellulose content and a higher lignin content than if the specimens had been rigorously screened to exclude all compression wood.

Although no published data are available defining the chemical constituents of compression wood in lodgepole pine stemwood, a wealth of data are available for other conifers, including a number of hard pines. Based on all the published data Timell (1986, pp. 391 and 458) concludes, in part, that:

> In general, the difference in chemical composition between normal and compression woods of the majority of conifers is of a quantitative rather than qualitative nature. . . . Compression wood contains 30-40% more lignin and 20-25% less cellulose than normal wood.

> The middle lamella and primary wall (in compression wood) evidently have the same composition as normal wood, with a relatively low cellulose and high pectin content. . . . The distribution of lignin in the tracheids of compression wood is highly characteristic and sets the tissue apart from normal wood. The unusually high lignin and low polysaccharide contents of the S_2 layer are unique among wood cells.

Prevalence of Compression Wood and Effect on Mechanical Properties

Only one publication specific to lodgepole pine was found to compare mechanical properties of normal wood to that containing compression wood. Koch and Barger (1988) sampled a pair of lodgepole pines 3.5 to 4 inches in diameter from each of 28 public forests in six northwestern States of the United States, and took specimens of stemwood from 20 percent of tree height. Of the 56 trees, 14 (25 percent) had compression wood—usually accompanied by more than average pith eccentricity, as follows:

State and forest	Degree of compression wood	Pith eccentricity
		Inch
Colorado		
Gunnison, tree #1	mild	0.1
Gunnison, tree #2	mild	.1
Bureau of Land Management, tree #2	mild	.4
Idaho		
Challis, tree #1	mild	.2
Challis, tree #2	mild	.1
Panhandle, tree #1	moderate	.2
Panhandle, tree #2	moderate	.3
Oregon		
Fremont, tree #1	mild	.1
Fremont, tree #2	moderate	.1
Mount Hood, tree #1	pronounced	.3
Mount Hood, tree #2	pronounced	.5
Washington		
Wenatchee, tree #2	mild	.4
Wyoming		
Bridger-Teton, tree #2	mild	.3
Shoshone, tree #2	mild	.2

The 9-inch-long stem sections evaluated—each containing a knot cluster—were air-dried, lathe-turned to $2^1/_4$ inches in diameter, and tested to destruction in compression parallel to the grain. Specimens containing compression wood (14 in number) had significantly lower properties—adjusted to a wood moisture content of 10 percent of ovendry weight—than those without compression wood (42 in number), as follows:

Property	No visible compression wood	Visible compression wood
	Psi	
Modulus of elasticity	1,270,000	940,000
Maximum crushing strength	5,920	5,250
Proportional limit	4,130	3,030

Knots and Compression Wood

Because compression wood is associated with knotwood, albeit in ways not entirely clear, the percentage of knotwood in stemwood is of interest. No data are available for North American stands of lodgepole pine, but Hakkila and Panhelainen (1970) sampled lodgepole pine (var. *latifolia*) stands in Finland established from seed mainly obtained between latitudes 50 and 51 degrees in Alberta and British Columbia. The trees had mean age of 40 years, mean d.b.h. of 5.0 inches, mean height of 44 feet, and crown ratio of 52 percent. They found that the percentage of knotwood in stems from South Finland (0.98 percent) was significantly less than the percentage in North Finland (1.67 percent), and that the percentage of knotwood increases from about 0.4 percent near the butt to about 2.4 percent in the upper portion of the stem (fig. 7).

Timell's (1986, pp. 804-808, 926-930) survey of the literature suggests that branches of practically all conifer's branches have at least some compression wood, and most of them contain sizable amounts. Stemwood knots, because they are basal parts of branches, always contain some compression wood, and often have large amounts. Associated with the knotwood are significant amounts of stemwood compression wood—particularly in the stem immediately below the knot, as will be further discussed in the "Results" section of this report.

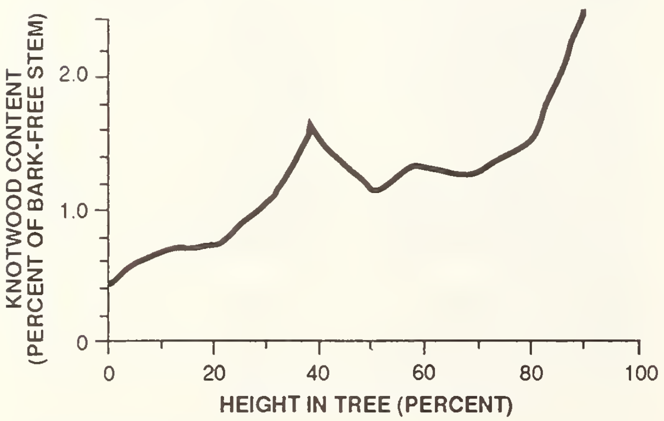


Figure 7—Longitudinal variation of knotwood percentage with height in stem of lodgepole pine (var. *latifolia*) grown in Finland from Canadian seed sources. (Drawing from Hakkila and Panhelainen 1970.)

Stem Form and Compression Wood

Sweep is common in conifers in general and is much evident in European plantations of lodgepole pine—particularly those of coastal origin. The literature—see Timell (1986 pp. 714-716, 758-773, 1270-1295)—indicates that crook is more strongly heritable than sweep and lean, which are often caused by environmental factors such as wind or snow.

Trees with a high incidence of sweep, crook, lean, and fork have more compression wood than straight trees—although the quantitative correlation between compression wood content and degree of these features is not outstanding. Scientists concerned with relating stem form to compression wood in lodgepole pines should find useful the following references:

Citation	Conclusion
Lines (1980)	Lodgepole pines in Europe, when exposed to wind, will develop a persistent lean rather than a broad sweep; such trees will have much compression wood.
Brazier (1966, 1980)	Compression wood is very common in British-grown lodgepole pine and most frequently occurs on the northern and eastern sides of the stem, away from the prevailing winds.
O'Driscoll (1980)	Results in Ireland similar to those reported by Brazier.

Timell's (1986, pp. 1745-1797) review of the literature related to the mechanism of compression wood action in righting a tree leads to his conclusion—in part—as follows:

> In vertically growing mature trees, the periphery and outer layers of the stem are in tension while the center is in compression. Leaning conifers, by contrast, are subjected to considerable compressive stress along both the lower and upper periphery, while the central portion is in tension. The compression on the lower side is partly due to the weight of the tree but largely to the active pressure exerted by the longitudinally expanding compression wood. The latter pressure is also responsible for the compressive stress on the upper side of the stem, a stress that is somewhat mitigated by the opposite, tensile stress caused by the weight of the tree.
>
> The mechanism by which compression wood is brought to expand along the grain in the living tree has not yet been fully clarified. The elongation could be caused by an increase in length over that of the fusiform initials in conjunction with an absence of gliding growth. It is more likely, however, that the elongation is associated with the deposition of lignin in the tracheid wall. Lignification probably results in a swelling of the cell wall, and when the microfibril

angle exceeds 30-40°, this swelling causes a longitudinal compressive stress. It has been estimated that this stress is five time larger than the tensile stress developed by normal wood and far in excess of any force that could arise in the active cambium. Regardless of the actual cause of the axial pressure exerted by compression wood, its origin must be sought in the differentiating tracheids.

European literature on lodgepole pine stem form is more extensive than that of North America, and originates principally from study of plantations in England, Scotland, Ireland, Sweden, and Finland. Some conclusions are referenced in the following paragraphs.

In British plantations of lodgepole pine, lean and basal sweep are common, particularly in stands originating from the coastal areas of Washington and Oregon (Davies 1980; Henderson and Petty 1972; Lines 1980; Lines and Booth 1972; Moss 1971; Remrod 1973).

In Ireland, the coastal variety of lodgepole pine has been favored over the inland type because of its more rapid growth, and in spite of its greater tendency toward basal sweep and stem sinuosity (Carey and Griffin 1981; Fitzsimons 1982; Lines 1957; Lynch 1980; Mooney 1966; O'Driscoll 1980; Pfeifer 1982).

In Sweden, variety *latifolia* is preferred over the coastal variety because of its rapid height and radial growth, but southern provenances are susceptible to stem malformation from wind and snow, and lodgepole pines planted in southern Sweden have shown a high incidence of bend, crook, forks, sinuosity, and coarse branches (Blomquist 1981; Fryk 1980, 1981; Hagner 1971, 1983; Karlman 1981; Lindgren 1980).

In southern Finland, lodgepole pine in 50-year-old stands yielded about the same volume of sawlogs as did *Pinus sylvestris*, in spite of lodgepole having more forked and multistemmed boles, and somewhat more crooked stems, than Scots pine (Lahde and others 1982).

Radial and Height Distribution of Compression Wood In Stems

The literature on compression wood distribution in coniferous stems is voluminous (see Timell 1986, pp. 773-822), but none of the published studies contain information specific to lodgepole pine. The reader is therefore referred to the "Results" section of this report.

Effect of Compression Wood on Warp in Lumber

Literature is abundant on longitudinal shrinkage of compression wood, but none of the published data are specific to lodgepole pine. Data on other hard pines, however, suggest that compression wood shrinks about tenfold (fourfold to fortyfold) more than normal wood of the hard pines (Timell 1986, p. 516). This disparity in longitudinal shrinkage between compression wood and normal wood can cause severe drying distortion in lumber.

Stemwood-average analysis of varieties *latifolia* and *murrayana* sampled from the same 279 lodgepole pine trees that were used in this study of compression wood yielded mean values of longitudinal shrinkage—green to ovendry—as follows (Wiedenbeck and others, in press):

	Radial position in tree	
Variety	Corewood	Mature wood
	- - - - - - - *Percent* - - - - - - -	
Latifolia	0.472	0.145
Murrayana	1.109	.243

Specimens for the foregoing analysis were not selected to totally exclude compression wood, so they more-or-less represented the natural mix of normal and compression wood. The shrinkage values suggest that the *murrayana* stems had more compression wood than the *latifolia* stems; this is consonant with findings reported in the "Results" section.

Two references were found relating warp in sawn lodgepole pine to compression wood content.

Malcolm's (1968) data do not expressly include correlation between compression wood content and lumber warp, but he implies such a relationship. In his study, 8-foot butt sections from small lodgepole pine sawlogs (variety and geographic area not specified, but probably var. *latifolia* from the Rocky Mountain region of the United States) were sawed into 2 by 4 studs and kiln dried to evaluate warp as related to stump height and degree of crook in the butt section of each bole. Malcolm found that studs cut from crooked butt sections warped more than those from straight butt sections—probably mainly attributable to greater compression wood content in the crooked butts. In trees with crooked butt sections, stud warp was minimized if the stud log was taken starting 3 or 4 feet above normal stump height. Malcolm concluded, therefore, that to minimize stud warp the first 3 or 4 feet of the butt ends of lodgepole pines with crooked lower boles should be chipped for pulp rather than sawn for lumber.

Posssibly stimulated by Malcolm's (1968) findings, Hallock (1969) studied warp in 2 by 4 studs cut from 8-foot lodgepole pine logs 6 to 12 inches in diameter obtained from the vicinity of West Yellowstone, MT. The logs, limited in sweep to 1 inch or less in the length of the log, were inspected on the sawn ends and classified as containing compression wood or not containing compression wood. Hallock found that no difference in yields of grade 1 studs or in their average warp could be attributed to the presence or absence of visually evident compression wood. He commented that: "because the warping effect of compression wood especially if located along one edge or face of a stud can hardly be denied, the only rational conclusion is that compression wood is not easily identifiable visually on the log ends in lodgepole. Thus it is possible that a substantial part of the sample classified *compression-wood absent* actually contained compression wood."

The authors of this paper, after light-table analysis of 2,790 lodgepole pine stem sections, concur with Hallock that compression wood is not easily identifiable on the ends of lodgepole pine logs in a woods or mill environment.

GENERAL STUDY PROCEDURE

Locating and Selecting the 243 *Latifolia* Trees

The sample area spanned from 40 to 60 degrees (inclusive) at 2.5-degree intervals; the width of the sample area was 10 degrees of longitude, with sample area shifting 2.5 degrees west for each 2.5 degrees shift north in latitude (fig. 1). Sample band width was 0.5 degree of latitude on each side of the nominal latitude line; each latitude band was 1 degree deep in the north-south direction (60 nautical miles), and 10 degrees of longitude wide in the east-west direction.

Within each of these nine latitudinal sampling bands, natural unthinned stands were identified with the following constraints: adjacent to road traversable by pickup truck; within boundaries of National or Provincial forests; and containing some more-or-less level benches or flats.

It was found that at least nine such stands could be identified within each sampling band. The identified stands were ranked by elevation, and then the three highest, the three most intermediate, and the three lowest were selected for sampling. These elevational zones were highest in the south and lowest in the north; elevational zone width was broadest at midlatitude (fig. 2).

On a bench or flat typical of each of these selected stands, single trees 76 mm, 152 mm, and 228 mm in d.b.h. and free of insects and diseases were taken that in the collector's view typified within-stand trees of these diameters on that bench or flat. Thus 27 *latifolia* trees were taken from each of the nine latitudes—3 diameters x 3 elevations x 3 replications, for a total of 243 trees.

It is important to note that this sampling scheme resulted in selection of 76-, 152-, and 228-mm trees that were of approximately the same age, because most of the stands were of fire origin. Thus, most of the small-diameter trees were suppressed, while the larger trees were the fast growers (table 1).

Locating and Selecting the 36 *Murrayana* Trees

The sample areas extended from 37½ to 45 degrees latitude at 2.5 degree intervals; trees were sampled at 37½, 40, 42½, and 45 degrees—but only at one longitude per latitude (fig. 1).

The same three constraints on location applied to *latifolia* also applied to *murrayana*, but *murrayana* was sampled only from midelevation as follows:

Latitude	Elevation	
Degrees	*Meters*	*Feet*
37½	2,402	7,880
40	1,676	5,499
42½	2,006	6,581
45	1,148	3,766

Thus nine *murrayana* trees were taken from each of the four latitudes—3 diameters x 1 elevation x 3 replications, for a total of 36 trees.

Field and Laboratory Work

For a complete description of the field work see Koch (1987, p. 9). See table 1 for summary information on the trees collected.

Stem Procedure—In the field the stem was shorn of branches so that it was complete from 152-mm-high stump to apical tip. By stretching a taut string between the 10- and 70-percent stem levels, the maximum crook was measured and recorded together with the stem level at which it occurred.

From the 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, and apical-tip level of the stem a pair of disks were removed—one 50 mm thick and bagged in polyethelene for laboratory determination of moisture content and specific gravity, the other 75 mm thick and air-dried for laboratory determination of additional properties.

Also transported from field to laboratory were two stem sections with bark in place—the first between stem levels 10 and 20 percent, and the second between 20 and 30 percent. In the laboratory these two stem sections were debarked and both wood and bark air dried and stored.

In the laboratory the number of annual rings at stump height was recorded, and the characterization disks air dried and stored. Each moisture disk was weighed green, its volume measured by water immersion, and its bark thickness (as measured by diameter tape before and after debarking) recorded. The debarked disk was weighed and its volume recorded. Heartwood was indicated by application of ferric chloride solution (10 g FeCl in 90 g water) and split away from the sapwood, heartwood diameter was measured, and heartwood weight and volume recorded. The ovendry weights of bark, sapwood, and heartwood of each disk were then recorded.

Determining Compression-Wood Content—From each of the 2,790 characterization air-dried disks of stemwood (10 disks from each of the 243 *latifolia* trees and 10 disks from each of the 36 *murrayana* trees) a slice 3 mm thick was accurately cut with a smooth-trim saw. Each disk was placed on a light table to reveal its compression wood content using the method of Pillow (1941). The disk outline and the outline of the compression wood present were delineated on a transparent sheet of appropriate size. A dot grid was then superimposed on the transparency, and a count made of the dots within the entire disk and within the areas of delineated compression wood. From these counts, six columns of data were derived:

1. Number of the dots within each entire stemwood disk.
2. Number of dots within the areas of compression wood delineated on each disk.
3. The percentage of each disk area represented by compression wood.
4. The total number of dots within the entire 10 disks of each tree.
5. The number of dots within the compression wood content of all 10 disks of each tree.
6. The percentage of the entire stemwood of each tree represented by compression wood.

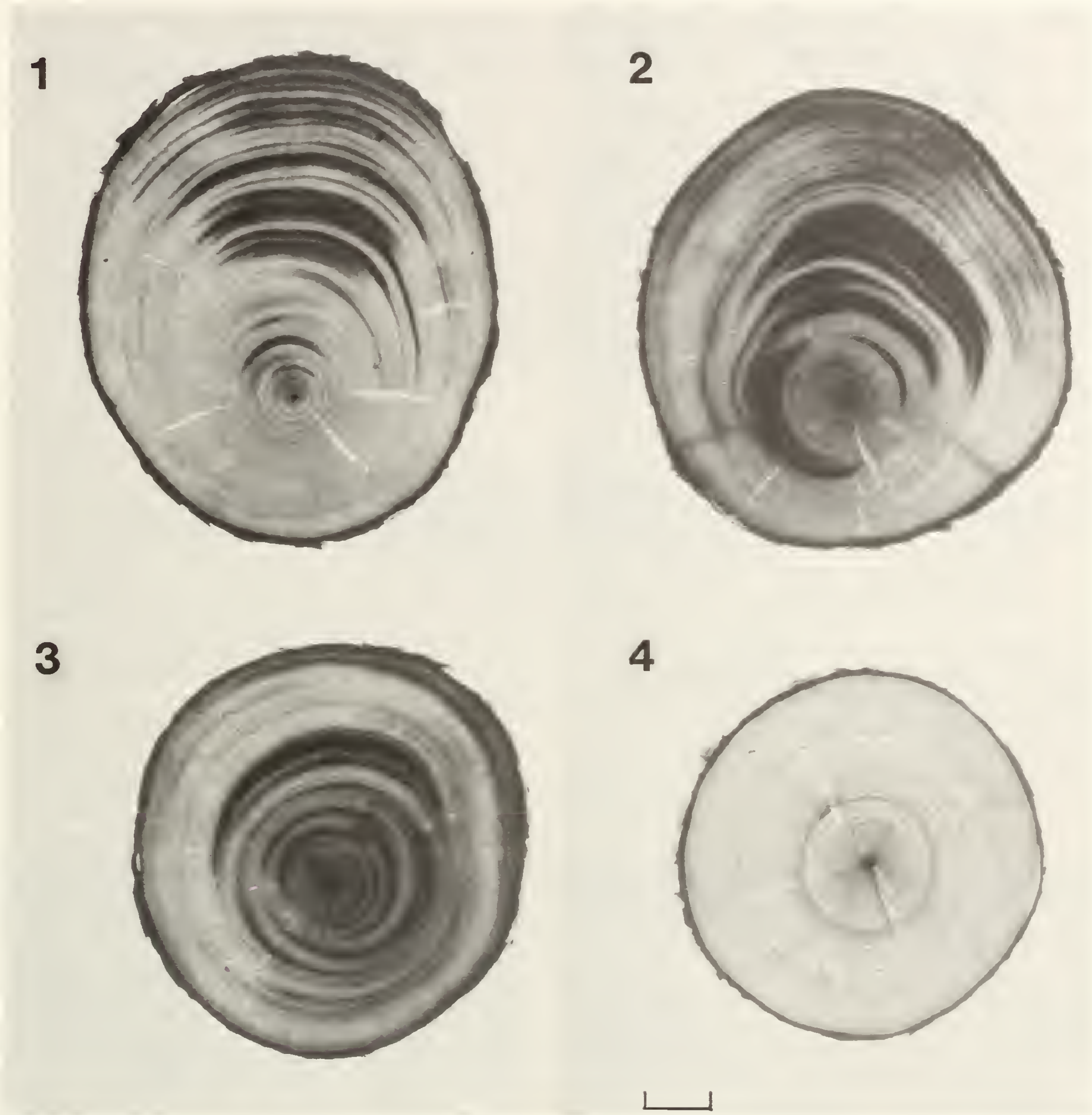


Figure 8—Compression wood patterns (dark areas) in lodgepole pine as viewed by transmitted light: (1) usual development in eccentric stem; (2) large areas of compression wood on opposite sides of pith; (3) circling concentric streaks of compression wood from pith to bark; (4) disk with almost no compression wood. The scale mark shows 1 cm.

The data from items 3 and 6 were entered on master computer-input data sheets, item 3 showing trends by height in each tree, and item 6 being a tree-average value.

Additionally, a code number was entered to designate the pattern in which the compression wood appeared using a classification similar to that of Boone and Chudnoff (1972); see figure 8:

1 = usual eccentric
2 = opposite
3 = concentric
4 = almost none or none

Also, a number was entered designating the absence or presence of knots:

0 = no knots
1 = knot or knots present in section

From these data, for each tree an arithmetic mean of the volume percentage of compression wood in sections with knots was derived and compared to the volume percentage of compression wood in those sections without knots.

Because the disks were taken to avoid obvious knot clusters (inclusion of which would have confounded clear-wood specific gravity determinations), total compression

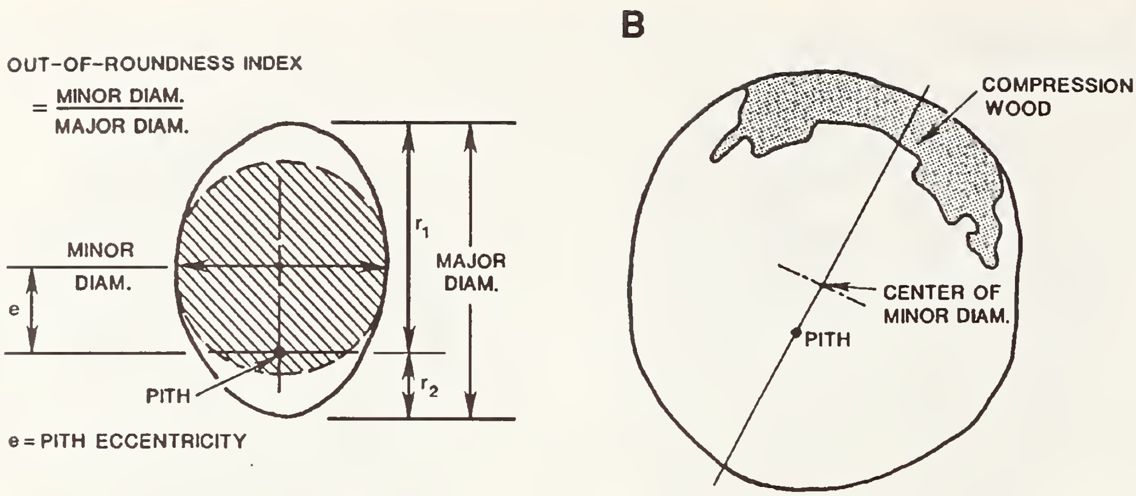


Figure 9—(A) Definition of section maximum diameter (maximum caliper inside bark, air dry), minor diameter (the diameter of the largest circle that could be inscribed within the section), r_1, r_2, out-of-roundness index, and pith eccentricity (e). (B) Section illustrating the typical case in which a line projected through pith and minor-diameter center intersects the compression-wood area on the r_1 side only.

wood associated with immediate proximity to knot clusters in the stemwood was not evaluated.

If, as reported by Hakkila and Panhelainen (1970), knotwood comprises about 1$^1/_3$ percent of lodgepole stemwood, and if associated compression wood is twice the knotwood volume, then compression wood related to knotwood might be about 2$^2/_3$ percent of stemwood volume; this computation is based on speculation, however. The study was not designed to ascertain the percentage of stemwood volume represented by knot-associated compression wood, however, since obvious knot clusters were avoided if practical when sample sections were taken.

Determining Pith Eccentricity—Pith eccentricity of each disk (fig. 9) was determined by overlaying each bark-free disk with a transparency containing concentric circles inked at 2-mm intervals of radius. The rings were placed to be as nearly as possible coincident with the stemwood section to include the largest ring possible, and the eccentricity of the pith (from the center point of this largest included ring) measured to the nearest millimeter. An arithmetic average of eccentricities of the 10 disks (levels 0, $^1/_{10}$, $^2/_{10}$, $^3/_{10}$, $^4/_{10}$, $^5/_{10}$, $^6/_{10}$, $^7/_{10}$, $^8/_{10}$, and $^9/_{10}$) provided a statistic representative of the tree average.

At the same time the major (major caliper) and minor (largest circle contained within the section) diameters of each disk were recorded (fig. 9) and the minor diameter expressed as a proportion of the major diameter—which provided a measure of the out-of-roundness of each section. An unweighted arithmetic mean of these ten statistics for each tree provided a tree-average index of stemwood out-of-roundness.

Recorded on the master computer-data input sheets, was the following information on the air-dried disks:

1. Pith eccentricity of each disk, millimeters
2. Tree-average pith eccentricity, millimeters
3. Index of out-of-roundness of each disk (minor diameter/major diameter)
4. Tree-average index of stemwood out-of-roundness

Additionally, on the transparency tracing of each section, a line was drawn from the pith through the centerpoint of the minor-diameter circle (fig. 9) and values for r_1 and r_2 recorded. From these values the ratios r_1/r_2, and e/r_1 were computed. When extended across the section, this line usually passed through compression wood areas within the section—but not always. Therefore the following code was used to record the situation:

0 = line missed all compression wood area
1 = line passed through compression wood areas on r_1 side
2 = line passed through compression wood areas on r_2 side
3 = line passed through compression wood areas on both r_1 and r_2 sides
4 = no compression wood in section.

Statistical Analysis

Analysis of variance was made in three groupings (table 3): *latifolia* throughout its principal latitudinal range of 40 through 60 degrees; *murrayana* through its primary latitudinal range of 37$^1/_2$ through 45 degrees; and *latifolia* compared to *murrayana* at the three common latitudes of 40, 42$^1/_2$ and 45 degrees (medium elevation only).

For each of the two varieties, standard deviations for measured tree characteristics were noted—usually by diameter class, with all other factors pooled.

Correlations of interest observed in *latifolia* between tree characteristics (including those described in Koch [1987]) were also determined.

Table 3—Analysis of variance format

Source	Degrees of freedom
Latifolia	
Latitude (L)	8
Elevation (E)	2
Diameter (D)	2
L x E	16
L x D	16
E x D	4
L x E x D	32
Error	162
Total	242
Murrayana	
Latitude	3
Diameter	2
L x D	6
Error	24
Total	35
Latifolia* compared to *Murrayana	
Variety (V)	1
Latitude	2
Diameter	2
V x L	2
V x D	2
L x D	4
V x L x D	4
Error	36
Total	53

RESULTS—GENERAL OBSERVATIONS ON ANATOMY

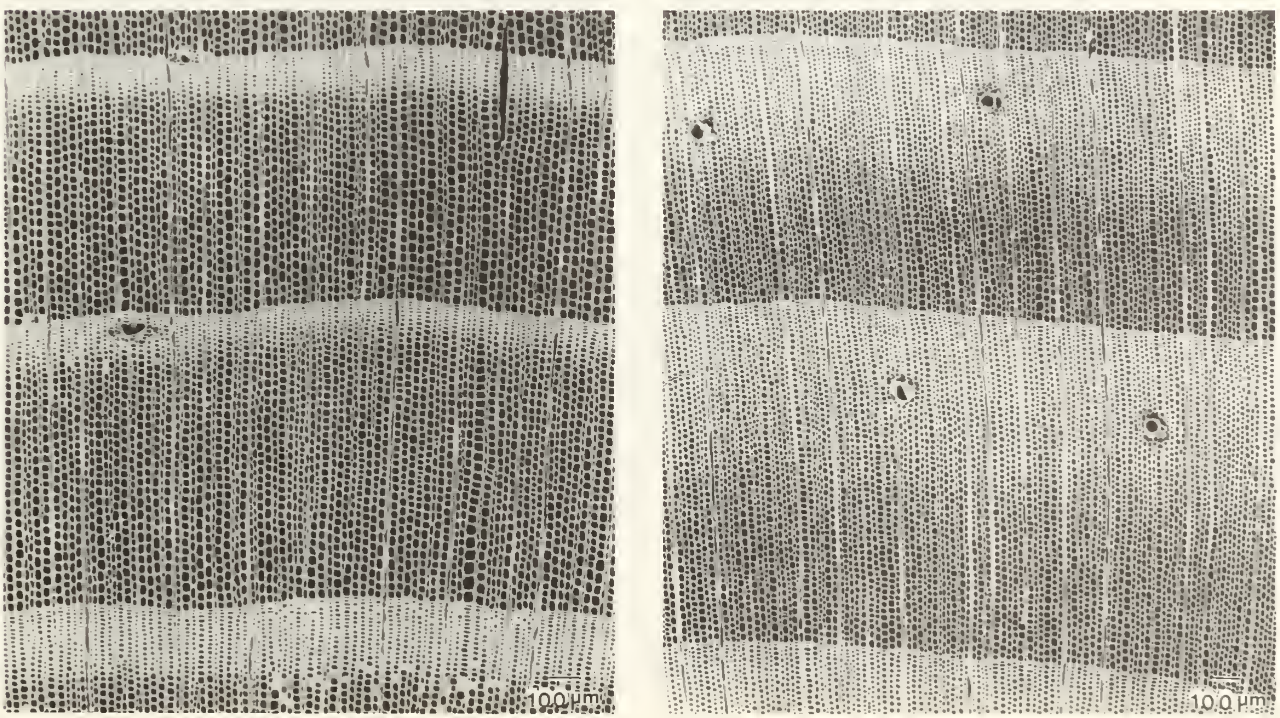
Cellular Structure and Wood Color

The transition from earlywood to latewood is gradual in compression wood (fig. 10), whereas it is usually abrupt in normal wood. As noted previously, pronounced compression wood in transverse section (fig. 11a) is characterized by roundness of cells, presence of intercellular spaces, checks in the inner portion of the secondary wall, and (fig. 11b) absence of the S_3 layer. Mild or moderate compression wood may display only two or three of these four attributes.

The color of normal lodgepole pine sapwood viewed in thin sections over a light table is light amber. Compression wood is discernible as more-or-less opaque areas—ranging in color from orange smudges (mild), to brown areas (moderate), to nearly black masses (pronounced). Micrographs of areas containing these colorations confirmed these degrees of compression wood severity.

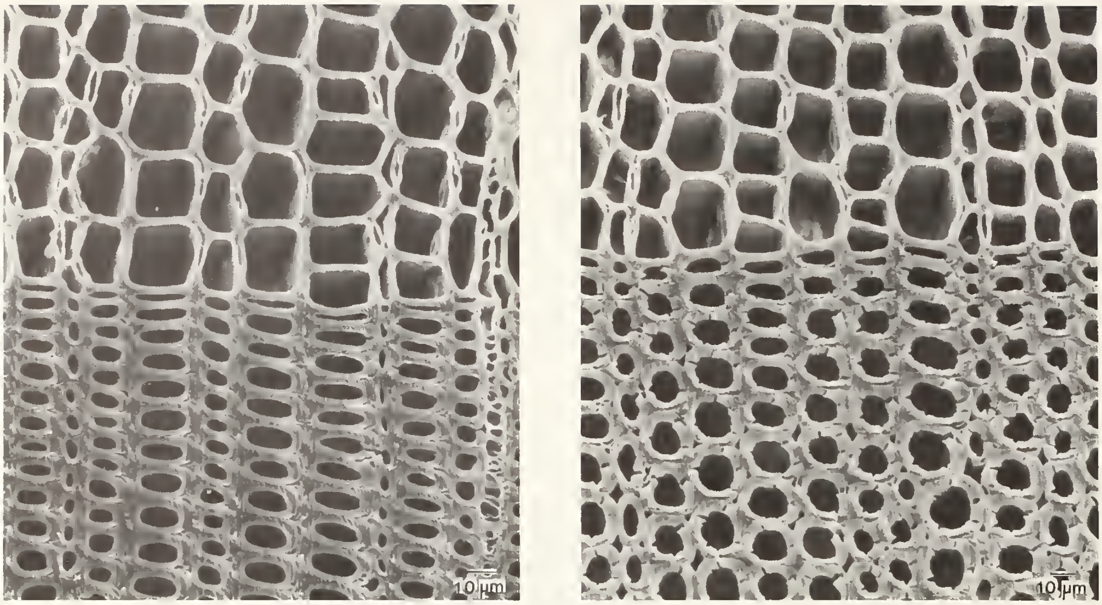
Patterns of Compression Wood

Patterns of compression wood can be classified as shown in figure 8, with most sections developing compression wood on the r_1 side (fig. 9 right and table 4), and most showing primarily annular patterns developed over less than 180° segments. When compression wood is mild, it is usually concentrated in the latewood of annual rings.



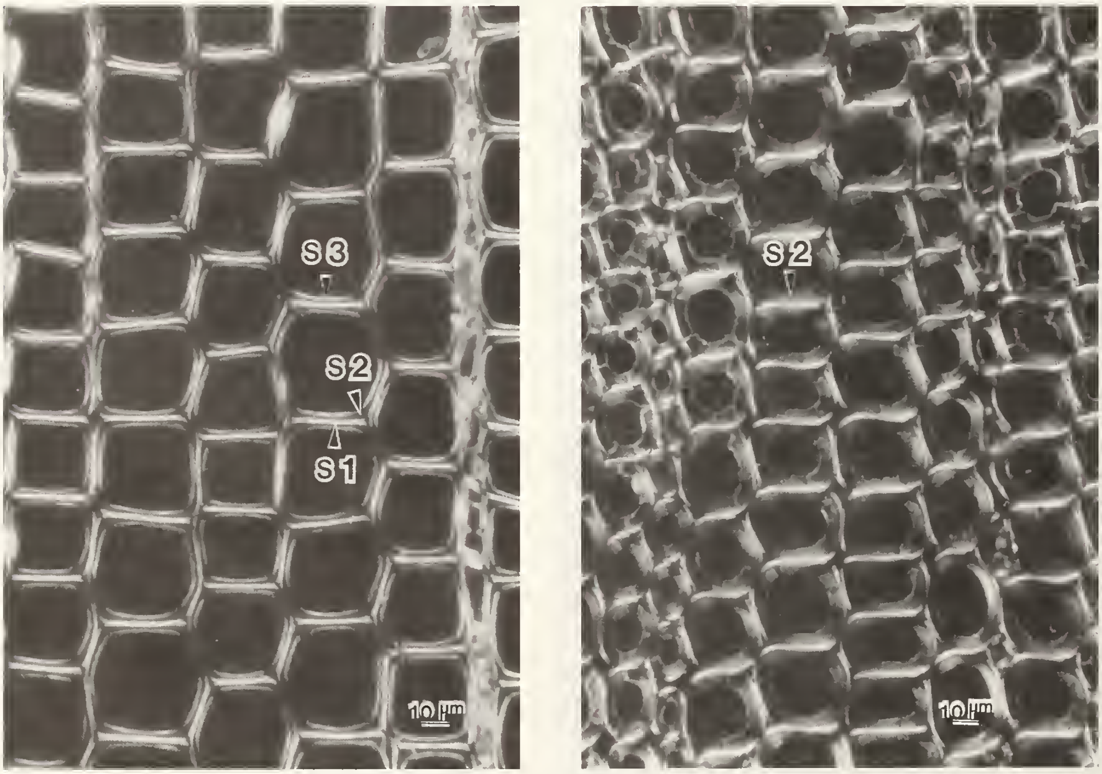
A B

Figure 10—Photomicrographs of cross sections of normal lodgepole pine wood (A) and compression wood (B). In normal wood the transition in cell size and wall thickness is abrupt between earlywood and latewood; compression wood exhibits a gradual transition in these dimensions.



A B

Figure 11a—Scanning electron micrographs of lodgepole pine normal wood (A) and compression wood (B). The earlywood tracheids at the top of each micrograph are similar in size and shape. The latewood tracheids show significant differences, however. Rounded tracheids, intercellular spaces, and "checked" walls are typical of compression wood—in marked contrast to normal latewood cells.



A B

Figure 11b—Polarized-light micrographs of lodgepole pine. (A) Normal wood displaying typical three-layered cell walls (bright S_3, dark S_2, and bright S_1). (B) Compression wood with S_3 layer absent.

As noted above it most frequently occurs (47 percent of all sections examined) in pattern #1, with intermittent years, or groups of years, affected (fig. 12). From such frequent patterns, one might infer that each lodgepole pine has a sensing and correction system that functions to maintain its stem in an erect mode. One could visualize this system operating much like the automatic pilot system of an airplane that maintains it in level flight. An observer of the controls of an airplane operating under the automatic pilot sees the controls periodically move to restore attitude; much of the time, however, the controls are in neutral. Thus it seems that the tree periodically signals for formation of compression wood to right itself, and then switches off the signal when the correction is complete.

Not infrequently trees overcorrect, possibly giving rise to pattern #2 (fig. 8).

Patterns in *Latifolia* Compared to Those in *Murrayana*—The most prevalent compression wood pattern in sections of both *latifolia* and *murrayana* was pattern #1 (fig. 8), which occurred in 47 percent of all sections examined in each variety. About one-third of the total sections in each variety had little or no compression wood, as follows:

Pattern (see fig. 8)	2,430 sections *latifolia*	360 sections *murrayana*
	Percent	
#1	47.0	47.2
#2	9.1	2.5
#3	9.3	6.7
#4	34.6	33.6
Total	100.0	100.0

Pattern Variation With Tree D.b.h.—*Latifolia* and *murrayana* trees 76 mm in d.b.h. have a smaller percentage of sections with little or no compression wood (and—in *latifolia*—a larger percentage with compression wood pattern #1) than trees 152 mm and 228 mm in d.b.h. (table 4).

Pattern Variation With Elevational Zone—Distribution of patterns of compression wood in *latifolia* appears to be unrelated to elevational zone, as follows:

Pattern in *latifolia*	Elevational zone		
	Low	Medium	High
		Percent	
#1	47.5	46.3	47.1
#2	9.6	8.4	9.4
#3	7.0	10.5	10.4
#4	35.9	34.8	33.1
Total	100.0	100.0	100.0

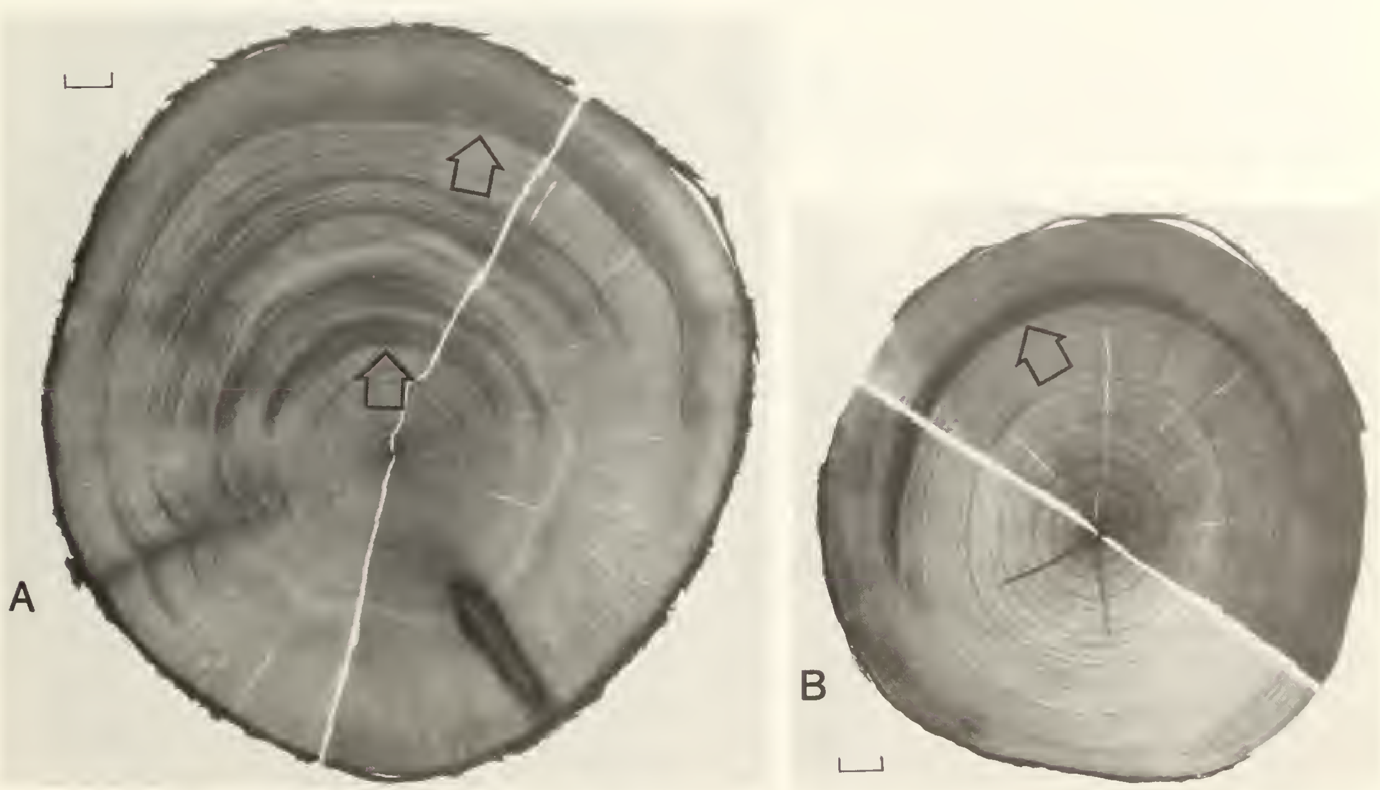


Figure 12—Frequently observed configuration of pattern #1 in lodgepole pine in which the compression wood has been formed in annular groupings during intermittent years. (A) Section at stump height from *latifolia* tree 152 mm in d.b.h. sampled at 45° latitude and medium elevation—replicate #1; multiple partial bands of compression wood. (B) Same tree sampled at 30 percent of tree height had only one band of compression wood. Scale mark shows 1 cm.

Table 4—Variation in percentage of four compression wood patterns in *latifolia* and *murrayana* transverse stem sections related to tree d.b.h.[1]

D.b.h.	1	2	3	4
mm		*Percent*		
		Latifolia		
76	51.4	9.5	11.1	28.0
152	47.3	5.8	8.3	38.6
228	42.2	12.1	8.5	37.2
Average	47.0	9.1	9.3	34.6
		Murrayana		
76	48.3	22.5	13.4	15.8
152	55.0	6.7	2.5	35.8
228	38.3	8.3	4.2	49.2
Average	47.2	12.5	6.7	33.6

[1]See figure 8 for pattern definitions. Data summarized from 2,430 sections of *latifolia*, and 360 sections of *murrayana*.

Pattern Variation With Latitude—With data on tree d.b.h. and elevational zones pooled, the percentage of the 2,430 *latifolia* sections with little or no compression wood was negatively correlated with latitude (tabulation following and fig. 13). Conversely, the percentage of sections with pattern #1 compression wood was positively correlated with latitude. Latitude was unrelated to percentage occurrence of compression wood patterns #2 and #3 in *latifolia* (fig. 13).

The 360 *murrayana* sections had different latitudinal variation; that is, percentages of sections with little or no compression wood were positively correlated with latitude (fig. 13), while percentages of sections with pattern #1 were negatively correlated with latitude as follows:

	Compression wood pattern			
Latitude	1	2	3	4
Degrees		*Percent*		
		Latifolia		
40	41.1	10.7	16.3	31.9
42.5	47.8	11.5	11.5	29.2
45	41.5	11.1	4.8	42.6
47.5	42.2	9.3	6.3	42.2
50	38.2	5.9	14.4	41.5
52.5	56.7	7.8	5.5	30.0
55	45.6	5.9	12.6	35.9
57.5	45.6	14.0	5.2	35.2
60	64.1	5.9	7.0	23.0
		Murrayana		
37.5	55.5	10.0	6.7	27.8
40	45.5	17.8	8.9	27.8
42.5	53.3	7.8	4.5	34.4
45	34.4	14.4	6.7	44.5

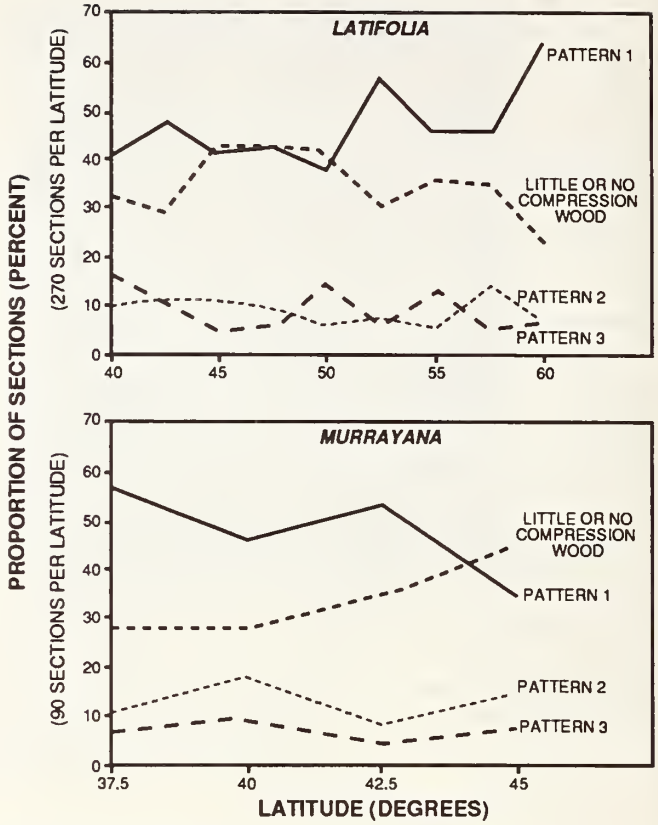


Figure 13—Compression wood patterns in transverse stem sections from 243 *latifolia* and 36 *murrayana* trees related to latitude. See figure 8 for pattern definitions.

In both varieties, sections sampled at 45 degrees through 50 degrees latitude had the greatest proportion of sections free of compression wood (fig. 13).

Pattern Variation With Height in Tree—In both *latifolia* and *murrayana* incidence of compression wood pattern #1 dominates near ground level, but incidence of this pattern diminishes with height in tree (fig. 14). Conversely, sections free of compression wood are infrequent in the lower stem, but upper stem sections are more frequently free of compression wood. Neither pattern #2 nor pattern #3 are descriptive of more than 20 percent of the sections analyzed, and correlation of these patterns' incidence with height is weak (fig. 14). Average values partitioned by percentage height in tree above a 152-mm-high stump top (with data on tree d.b.h., latitude, and elevational zone pooled) are summarized as follows:

Percentage of tree height	Compression wood pattern 1	2	3	4
	- - - - - - - - Percent - - - - - - - - -			
	Latifolia			
0	62.1	5.8	8.6	23.5
10	56.4	10.3	13.2	20.1
20	56.0	6.2	11.1	26.7
30	52.7	8.2	12.4	26.7
40	46.9	8.2	9.1	35.8
50	44.4	5.4	12.8	37.4
60	40.3	9.9	9.1	40.7
70	38.3	11.9	7.0	42.8
80	37.4	10.3	6.6	45.7
90	35.0	15.2	3.3	46.5
	Murrayana			
0	69.4	2.8	16.7	11.1
10	61.1	11.1	13.9	13.9
20	50.0	16.7	8.3	25.0
30	55.5	13.9	5.6	25.0
40	44.4	16.7	8.3	30.6
50	50.0	13.9	2.8	33.3
60	27.8	16.7	5.5	50.0
70	50.0	8.3	0.0	41.7
80	41.7	11.1	0.0	47.2
90	22.2	13.9	5.6	58.3

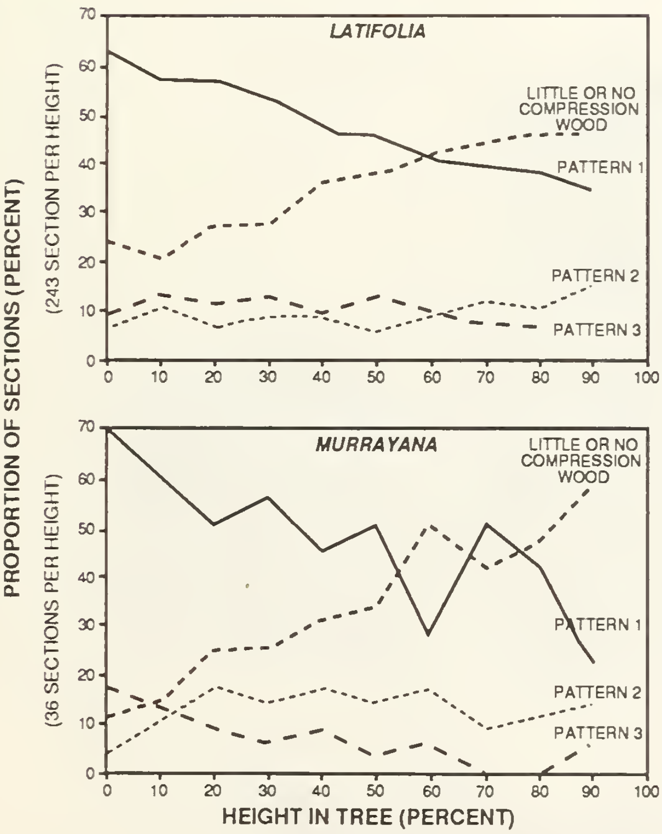


Figure 14—Compression wood patterns in transverse stem sections from 243 *latifolia* and 36 *murrayana* trees related to percentage height from 152-mm-high stump top to apical tip. See figure 8 for pattern definitions.

RESULTS—COMPRESSION WOOD CONTENT AND DISTRIBUTION

Knots and Compression Wood

In transverse sections of stems containing knots and viewed over a light table—or even under the light microscope—we found it extremely difficult to distinguish shadings caused by grain deviations from those caused by compression wood. Our impression is that adjacent to knot perimeters (viewed in stem transverse section) there is less compression wood present than the shading from light impedence suggests. The grain direction within the stemwood knots, and their resin content, precluded any light-table analysis of their compression wood content, and knot area was excluded from all totals of compression wood area in stem cross sections. Figure 15 is included to give the reader some idea of the grain distortions around lodgepole pine knots.

In comparing the compression wood content—by tree average—of sections with knots and sections without knots, the data are inconclusive as to whether presence of knots in cross sections increases or decreases the percentage of compression wood in the sections. Tree-average values of sections with no knots and sections with knots were as follows:

D.b.h.	No knots	Containing knots
mm	*Percent compression wood*	
	Latifolia	
76	7.3	5.7
152	3.7	2.8
228	4.8	4.3
All 243 trees	5.3	4.2
	Murrayana	
76	10.6	14.2
152	4.6	3.4
228	2.5	2.9
All 36 trees	5.9	7.0

The study was focused on transverse sections, but a few longitudinal sections through knots and pith were examined to confirm the impression that compression wood often forms in stems immediately below branches. Not always present, such compression wood was evident to some degree in about 30 percent of the longitudinal sections examined (fig. 16).

Surprisingly, tree-average percentage of compression-wood volume in stems of the 243 *latifolia* trees in the main study was negatively (and significantly) correlated with number of live and dead branches; that is, trees with least numbers of branches had most percentage of compression wood. The relationship was weak, however, accounting for only about 2 percent of the observed variation.

Figure 15—Transverse section through knot of *latifolia*. Grain deviations in vicinity of knot preclude accurate assessment of compression wood content by light-table method.

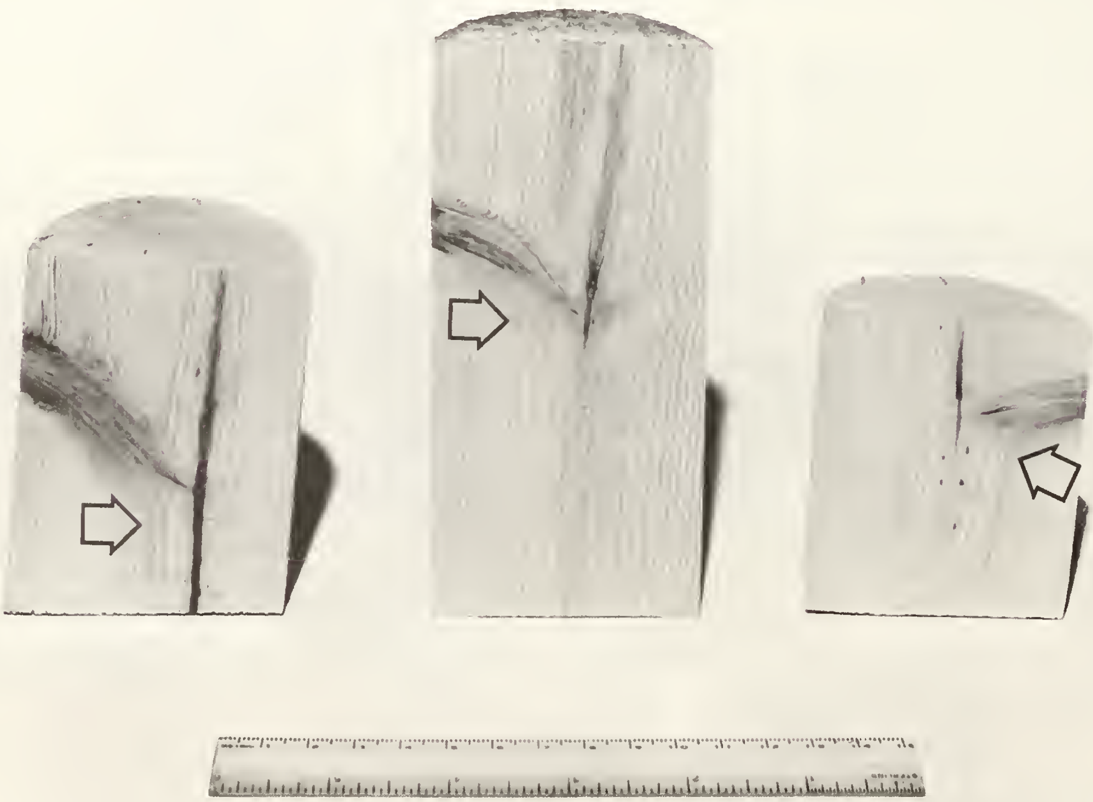


Figure 16—Longitudinal sections of *latifolia* showing compression wood (arrows) formed below branches. Sections measure about 65 mm in diameter.

Geographic Variation and Variation Among Trees by D.b.h. Class and Elevational Class—*Latifolia*

Trees 76 mm in d.b.h. had significantly higher stem-average percentage of compression wood than those 152 mm or 228 mm in d.b.h.; the 152-mm trees had the lowest percentage, as follows:

Tree d.b.h.	Number of trees	Compression wood content
mm		*Percent*
76	81	7.5
152	81	4.0
228	81	5.2

With data from trees of all diameters pooled, tree-average percentage compression wood did not vary significantly by elevational zone; averages were as follows:

Elevational zone	Percentage compression wood
Low	5.1
Medium	5.6
High	5.9

Similarly, with data from the 243 *latifolia* trees of all diameters and elevations pooled, tree-average percentage of compression wood did not differ significantly with latitude, as follows:

Latitude	Compression wood content
Degrees	*Percent*
40	5.6
42.5	5.3
45	3.8
47.5	6.0
50	5.6
52.5	6.1
55	7.2
57.5	4.7
60	5.6

There were no significant interactions among the three factors: d.b.h., elevational zone, and latitude. Table 5 summarizes the data by these three factors, displaying means, standard deviations, and ranges. With data from all 243 trees pooled, the mean tree-average percentage of compression wood was 5.5 percent, with range from 0.0 to 36.1 percent. Among these, only one stem was free of compression wood—a 152-mm tree from latitude 57.5 degrees in the low elevational zone (table 5).

Each sampling band (fig. 1) was 10 degrees of longitude wide and was divided into 10 longitudinal zones. Neither longitudinal zone nor longitude (degrees) was significantly correlated with percentage of compression wood.

Table 5—Mean, standard deviation, and range in tree-average percentage compression wood in stems of *latifolia* by latitude, elevational class, and tree d.b.h.[1]

Elevational class	Tree d.b.h. 76 mm	152 mm	228 mm	All trees
	Percent			
		40° Latitude		
Low	9.24 (8.58)	8.25 (9.64)	7.55 (2.44)	8.35 (6.61)
	3.8-19.1	1.2-19.2	4.7-9.0	1.2-19.2
Medium	5.28 (0.71)	2.35 (1.57)	2.96 (2.75)	3.53 (2.11)
	4.5-5.8	0.5-3.3	0.3-5.8	0.3-5.8
High	6.63 (5.04)	2.02 (1.58)	5.71 (4.71)	4.79 (4.12)
	3.3-12.4	0.3-3.5	1.8-10.9	0.3-12.4
		42.5° Latitude		
Low	5.04 (1.02)	5.54 (3.25)	3.43 (1.37)	4.67 (2.07)
	4.2-6.2	2.3-8.8	1.9-4.4	1.9-8.8
Medium	6.23 (7.65)	0.85 (0.88)	13.47 (12.7)	6.85 (9.23)
	0.7-15.0	0.3-1.9	2.7-27.5	0.3-27.5
High	6.45 (5.29)	1.54 (1.13)	4.77 (2.12)	4.25 (3.62)
	1.1-11.7	0.4-2.6	2.5-6.7	0.4-11.7
		45° Latitude		
Low	6.21 (0.84)	2.46 (2.52)	0.93 (0.43)	3.20 (2.71)
	5.5-7.1	0.7-5.3	0.6-1.4	0.6-7.1
Medium	7.52 (2.61)	3.50 (2.44)	2.42 (1.77)	4.48 (3.07)
	5.2-10.3	1.9-6.3	1.2-4.4	1.2-10.3
High	6.75 (7.41)	1.36 (0.82)	3.13 (1.49)	3.75 (4.48)
	0.9-15.1	0.6-2.2	1.4-4.1	0.6-15.1

(con.)

Table 5—(Con.)

Elevational class	Tree d.b.h. 76 mm	152 mm	228 mm	All trees
	Percent			
		47.5° Latitude		
Low	1.74 (0.82)	2.59 (1.90)	11.57 (9.38)	5.30 (6.73)
	1.2-2.7	0.6-4.3	1.2-19.4	0.6-19.4
Medium	8.07 (7.70)	5.74 (5.52)	7.18 (1.37)	7.00 (4.89)
	2.4-16.8	2.2-12.1	6.2-8.7	2.2-16.8
High	9.63 (10.77)	3.27 (0.90)	4.18 (3.94)	5.69 (6.48)
	2.1-22.0	2.2-3.8	1.2-8.6	1.2-22.0
		50° Latitude		
Low	3.98 (3.11)	1.82 (2.13)	4.56 (2.76)	3.45 (2.65)
	1.0-7.2	0.5-4.3	1.6-7.1	0.5-7.2
Medium	6.31 (5.25)	7.72 (5.39)	6.39 (4.66)	6.81 (4.48)
	1.2-11.7	1.7-12.0	2.3-11.5	1.2-12.0
High	10.22 (9.59)	1.92 (0.89)	7.12 (4.79)	6.42 (6.49)
	1.9-20.7	0.9-2.7	2.0-11.4	0.9-20.7
		52.5° Latitude		
Low	7.34 (5.35)	5.77 (4.79)	1.48 (0.58)	4.86 (4.46)
	2.3-13.0	1.7-11.0	1.1-2.2	1.1-13.0
Medium	10.03 (7.79)	5.77 (2.81)	5.46 (2.90)	7.09 (4.91)
	1.1-15.4	4.0-9.0	2.3-8.0	1.1-15.4
High	12.14 (5.90)	4.27 (3.84)	2.88 (0.67)	6.43 (5.58)
	7.6-18.8	0.8-8.4	2.2-3.5	0.8-18.8
		55° Latitude		
Low	4.93 (4.56)	8.84 (4.79)	9.92 (6.22)	7.90 (5.08)
	0.6-9.7	3.8-13.3	4.2-16.6	0.6-16.6
Medium	10.98 (5.86)	6.59 (3.43)	1.86 (1.09)	6.48 (5.24)
	4.3-15.4	3.7-10.4	1.0-3.1	1.0-15.4
High	9.52 (13.54)	8.37 (8.88)	3.64 (0.75)	7.18 (8.54)
	0.8-25.1	3.0-18.6	3.1-4.5	0.8-25.1
		57.5° Latitude		
Low	5.48 (1.27)	0.91 (1.43)	3.24 (2.75)	3.21 (2.59)
	4.5-6.9	0.0-2.6	0.9-6.3	0.0-6.9
Medium	5.07 (1.78)	3.85 (2.36)	4.06 (1.26)	4.33 (1.70)
	3.6-7.1	2.1-6.5	2.6-4.8	2.1-7.1
High	2.79 (0.68)	2.59 (3.1)	14.19 (19.01)	6.53 (11.22)
	2.1-3.5	0.5-6.2	2.2-36.1	0.5-36.1
		60° Latitude		
Low	10.29 (6.30)	2.36 (1.79)	1.59 (1.33)	4.75 (5.35)
	3.0-14.4	0.4-4.0	0.5-3.1	0.4-14.4
Medium	7.19 (2.34)	2.34 (1.02)	2.93 (3.59)	4.15 (3.18)
	5.2-9.8	1.3-3.3	0.7-7.1	0.7-9.8
High	16.13 (6.72)	4.06 (3.50)	3.32 (0.30)	7.84 (7.29)
	8.6-21.6	0.5-7.5	3.1-3.7	0.5-21.6
Pooled	7.45 (5.87)	3.95 (3.92)	5.18 (5.68)	5.53 (5.41)
	0.6-25.1	0.0-19.2	0.3-36.1	0.0-36.1

[1]Entries in the body of the table show the mean percentage, followed by the standard deviation in parentheses; listed below these two statistics is the range.

Identification of Trees That Will Have High Stem-Average Compression Wood Content—*Latifolia*

Although tree-average percentage of compression wood was not significantly related to geographic location (latitude, longitude, and elevation), it was significantly correlated (0.05 level) with many other tree characteristics, as follows:

Sign of correlation and characteristic	r
Positive	
Tree-average pith eccentricity (e), by d.b.h.	
76 mm	0.492
152 mm	.371
228 mm	.228
Tree-average e/r_1, all values	.336
Tree-average e/r_1, by d.b.h.	
76 mm	.484
152 mm	.325
228 mm	.284
Stemwood-average specific gravity	.324
r_1/r_2 (see fig. 9 for definition)	.319
Average live-branch angle	.233
e/r_1 (see fig. 9 for definition)	.230
Cone weight (computed from the number and weight of cones on the first foot of the top 25 branches) proportion of complete-tree weight, ovendry basis	.128
Stump-root proportion of complete-tree weight, ovendry basis	.126
Negative	
Average live-branch diameter	–0.181
Sapwood moisture content, stem-average	–.178
Stem diameter at base of live crown	–.173
Diameter at breast height	–.169
Diameter at 152-mm-high stump	–.167
Length of live crown	–.161
Heartwood diameter at top of 152-mm-high stump	–.160
Tree height from 152-mm-high stump top to apical tip	–.158
Stump–average bark thickness	–.155
Stembark thickness at 152-mm–high stump top	–.149
Number of dead branches	–.144
Number of live branches	–.142
Average width of annual rings at top of 152-mm-high stump	–.141
Branch proportion of complete-tree weight, ovendry	–.129

Also of interest is the **lack** of significant correlation between percentage of compression wood content in *latifolia* stems with the following tree characteristics:

Latitude
Longitude (degrees)
Longitudinal zone
Elevation (meters)
Age at stump top
Maximum stem crook
Stemwood-average out-of-roundness index; that is, minor/major diameter, average for 10 heights in each stem
Crown ratio
Width of live crown
Number of cones on first foot of top 25 branches
Total weight of live branches, ovendry (including bark, but not foliage)
Total stump-root weight including bark, ovendry
Total stemwood weight, ovendry
Total sapwood weight, ovendry
Total heartwood weight, ovendry
Complete-tree weight, ovendry
Bark proportion of complete-tree weight, ovendry
Foliage proportion of complete-tree weight, ovendry
Stemwood proportion of complete-tree weight, ovendry
Stembark-average specific gravity
Stembark-average moisture content
Stemwood-average moisture content
Heartwood moisture content
Moisture content of complete tree
Stem taper to base of live crown, millimeters per meter
Stem taper within live crown, millimeters per meter

When evaluating entire stems of *latifolia* trees, highest proportion of compression wood content will be found in slow-growing, small-diameter (for example, 76 mm), short trees with little heartwood at stump height, large live-branch angle, high stemwood specific gravity, and a relatively high proportion of complete-tree weight represented by the stump-root system and by cones. Because compression wood is more dense than "normal" wood, it is logical that stemwood-average specific gravity of trees with much compression wood should be higher than specific gravity in trees with little or no compression wood.

Lowest stem-average proportions of compression wood will be found in fast-growing, tall trees with long crowns, comprised of many branches, which typically have large diameter but small branch angle (and a relatively high proportion of complete-tree weight represented by branches), high sapwood moisture content, much heartwood at stump height, thick stump bark, and a low proportion of complete-tree weight represented by the stump-root system. Stemwood in such trees will have lower specific gravity than the stemwood of trees with a high proportion of compression wood.

Variation of Compression Wood Content Within Tree Stems—*Latifolia*

Compression wood content varied significantly with percentage of height in *latifolia* trees, the relationship differing by d.b.h. class (table 6 and figs. 17 and 18).

Table 6—Variation in *latifolia* and *murrayana* of percentage compression wood, out-of-roundness index, pith eccentricity, minor diameter, compression wood area, and gross cross-sectional area with percentage height in tree from 152-mm-high stump top to apical tip (see figure 9 for definitions)

	Percentage of tree height									
D.b.h.	0	10	20	30	40	50	60	70	80	90
mm										
					Latifolia					
					Compression wood content (percent)					
76	11.1	8.7	7.3	5.8	6.3	5.2	5.3	6.0	7.3	6.3
152	5.2	5.2	4.3	3.7	2.9	2.7	2.5	2.1	2.9	4.0
228	6.0	7.5	5.9	5.4	3.5	2.9	3.9	2.9	3.9	5.4
					Out-of-roundness index					
76	0.88	0.91	0.92	0.92	0.92	0.92	0.91	0.91	0.89	0.87
152	.88	.91	.92	.92	.92	.92	.91	.91	.90	.88
228	.87	.91	.92	.92	.92	.92	.91	.91	.90	.90
					Pith eccentricity, *e* (mm)					
76	7.4	5.0	3.9	3.6	3.4	2.8	2.4	2.0	1.6	0.9
152	12.5	9.0	7.1	7.2	6.2	5.7	5.1	4.0	3.0	2.2
228	20.2	14.8	13.4	11.8	10.3	9.8	9.1	6.7	4.8	3.2
					e/r_1					
76	0.16	0.12	0.10	0.10	0.10	0.09	0.09	0.09	0.09	0.09
152	.13	.11	.10	.10	.10	.10	.10	.09	.09	.10
228	.14	.12	.12	.11	.11	.11	.11	.10	.10	.11
					r_1/r_2					
76	1.56	1.35	1.30	1.29	1.29	1.26	1.24	1.26	1.26	1.20
152	1.43	1.32	1.27	1.27	1.26	1.24	1.26	1.25	1.25	1.28
228	1.41	1.35	1.32	1.30	1.28	1.28	1.30	1.26	1.26	1.28
					Minor diameter (mm)					
76	69.1	65.7	62.8	59.0	54.6	49.4	43.2	35.7	27.0	16.0
152	142.1	128.4	121.5	114.3	107.6	98.4	87.7	73.5	56.9	33.0
228	215.5	192.9	182.3	172.5	159.2	145.6	129.4	108.4	81.8	46.5
					Compression wood area (mm^2)					
76	482	325	247	172	164	107	86	71	48	16
152	942	740	541	416	291	232	173	102	84	44
228	2,507	2,416	1,680	1,377	750	528	589	293	224	112
					Gross cross-sectional area of wood (mm^2)					
76	4,317	3,750	3,400	2,996	2,588	2,129	1,641	1,129	669	249
152	18,267	14,285	12,690	11,260	9,914	8,280	6,691	4,772	2,891	1,050
228	42,722	32,249	28,498	25,441	21,920	18,199	14,688	10,320	5,956	1,978
					Murrayana					
					Compression wood content (percent)					
76	22.7	17.6	15.6	10.0	12.8	7.3	5.5	9.2	4.6	9.1
152	10.0	8.2	2.6	3.4	3.0	2.3	2.8	1.6	6.4	2.1
228	6.4	2.6	2.2	2.7	3.5	2.0	.8	1.4	1.7	3.2
					Out-of-roundness index					
76	0.88	0.90	0.93	0.91	0.91	0.89	0.91	0.89	0.89	0.88
152	.87	.91	.92	.92	.92	.92	.91	.92	.91	.90
228	.86	.93	.92	.92	.92	.91	.91	.91	.92	.90
					Pith eccentricity, *e* (mm)					
76	9.3	6.8	6.3	4.1	3.8	2.9	2.2	2.0	0.9	0.6
152	19.3	8.9	8.1	6.0	5.6	5.7	4.3	3.0	2.8	1.3
228	22.6	13.1	12.4	13.8	9.7	7.8	7.1	6.4	2.6	1.9
					e/r_1					
76	0.20	0.16	0.16	0.11	0.12	0.10	0.09	0.10	0.07	0.08
152	.18	.11	.11	.09	.09	.10	.09	.08	.09	.09
228	.14	.11	.11	.13	.11	.09	.09	.10	.06	.08

(con.)

Table 6—(Con.)

D.b.h.	0	10	20	30	40	50	60	70	80	90
					Percentage of tree height					
mm										
					r_1/r_2					
76	1.76	1.49	1.48	1.34	1.34	1.26	1.22	1.30	1.24	1.17
152	1.78	1.36	1.29	1.23	1.26	1.27	1.23	1.20	1.29	1.18
228	1.57	1.29	1.35	1.36	1.25	1.24	1.25	1.31	1.12	1.20
					Minor diameter (mm)					
76	66.4	64.0	62.8	58.1	52.9	46.1	39.4	31.2	22.7	13.2
152	139.6	128.6	120.8	112.3	103.3	92.8	79.9	66.2	49.5	27.4
228	214.8	193.3	181.2	169.8	156.1	140.3	122.8	101.6	73.6	39.1
					Compression wood area (mm^2)					
76	895	647	541	303	325	141	75	78	20	14
152	1,926	1,178	328	362	273	177	181	53	115	7
228	2,940	804	627	666	742	336	106	125	67	42
					Gross cross-sectional area of wood (mm^2)					
76	4,008	3,635	3,391	2,940	2,468	1,916	1,380	875	461	166
152	17,912	14,301	12,481	10,832	9,204	7,474	5,644	3,859	2,210	700
228	42,623	31,702	28,250	24,696	20,815	17,113	13,150	9,090	4,736	1,447

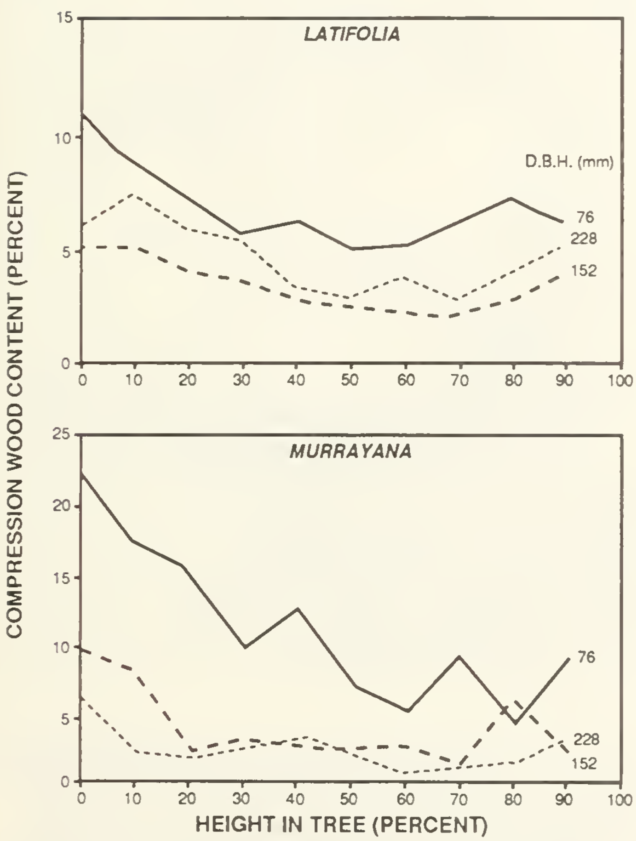


Figure 17—Variation of compression wood content with height in stems of *latifolia* (81 of each d.b.h.) and *murrayana* (12 of each d.b.h.) trees of three diameters.

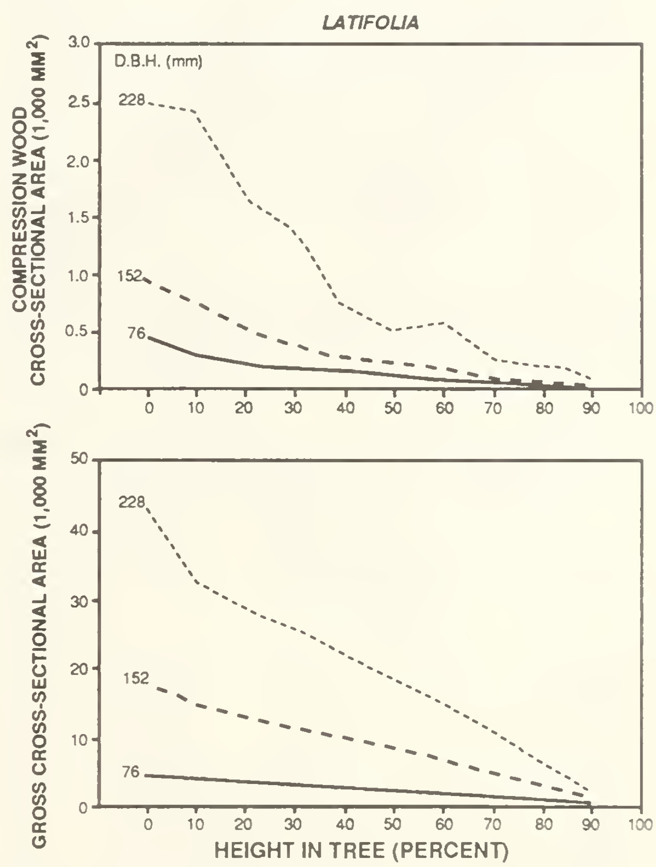


Figure 18—Variation with height in tree of compression wood cross-sectional area and gross cross-sectional area (bark-free) in *latifolia* trees of three diameters. See table 6 for numeric values.

When the percentage compression wood content of each of the 2,430 (243 trees x 10 heights) *latifolia* sections was correlated—and each of the 360 *murrayana* sections similarly correlated—with each section's other properties, some significant relationships were evident, as follows:

Section's characteristic correlated with the section's percentage of compression wood	*Latifolia* (n = 2.430) r	*Murrayana* (n = 360) r
Positive correlations		
r_1/r_2 (fig. 19)	0.378	0.518
e/r_1 (fig. 19)	.362	.489
Specific gravity of wood (fig. 20)	.299	.409
Pith eccentricity, e (fig. 20)	.187	.230
Negative correlations		
Out-of-roundness index (fig. 20)	–0.180	–0.188
Height above ground, meters	–.150	–.370
Moisture content of wood	–.136	–.309
Minor diameter	–.040	–.171

These correlations suggest that sections (or short logs) sampled in *latifolia* stems will tend to have high percentages of compression wood if they are out of round and close to ground level, and have eccentric piths, high specific gravities, and low moisture contents. Also, there is a weak tendency for small-diameter wood to have more percentage compression wood content than large-diameter wood.

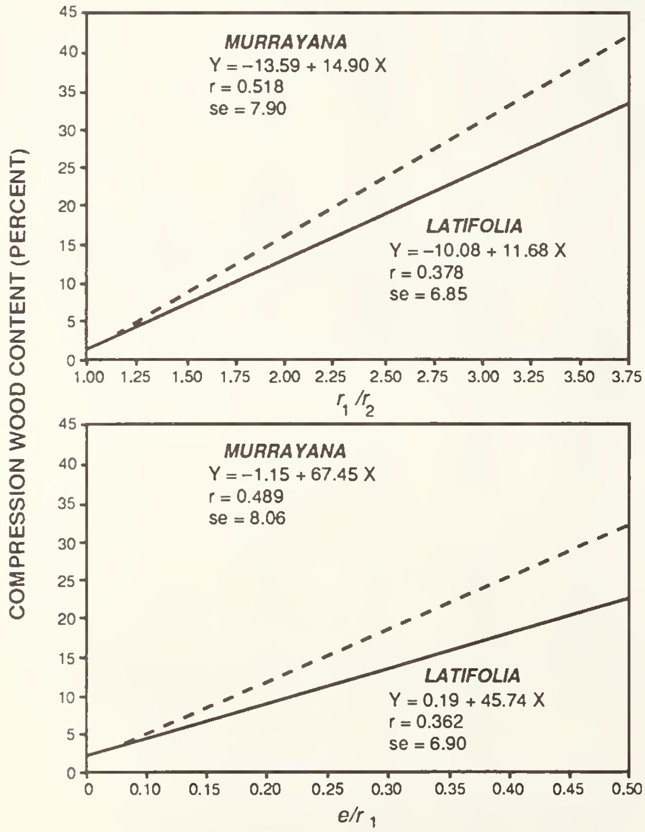


Figure 19—Regression equations relating compression wood content of individual stem sections in *latifolia* (n = 2,430) and *murrayana* (n = 360) to two measures of pith eccentricity (e/r_1 and r_1/r_2).

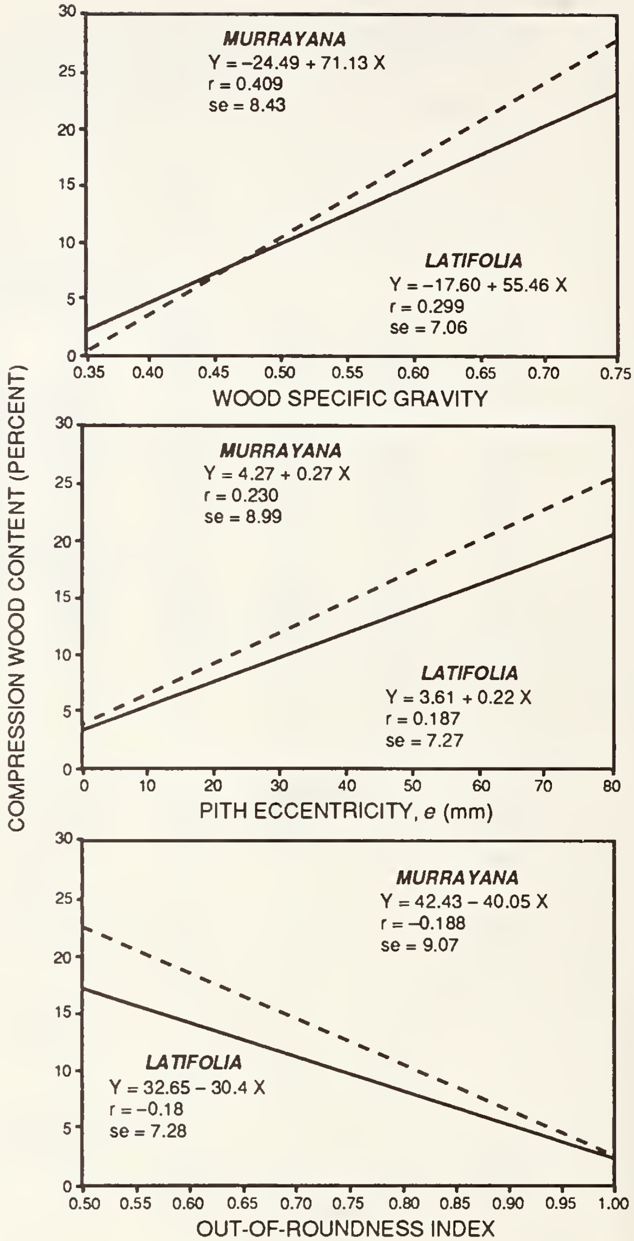


Figure 20—Regression equations for three section characteristics significantly related to compression wood content of individual stem sections in *latifolia* (n = 2,430) and *murrayana* (n = 360) trees. Wood specific gravity is based on green volume and ovendry weight.

Location of Sections Free of Compression Wood—See previous discussion of pattern #4 occurrence under heading "Results—General Observations and Anatomy".

Location Within Section Where Compression Wood Will Probably Be Concentrated—Analysis of all the sections that did contain compression wood indicated that the location of the major areas of compression wood in a section or log end—though not easily distinguishable visually—can usually be predicted. That is, a line projected from the pith through the center of the largest

circle that can be inscribed within the section will usually pass through the main area of compression wood on the r_1 side or on both the r_1 and r_2 sides (fig. 9), as follows:

Description of line intersection with compression wood area	Latifolia	Murrayana
	- - - - - Percent - - - - -	
Intersection on r_1 side only (fig. 9, right)	61.8	68.6
Intersection on r_2 side only	5.5	5.1
Intersection on both r_1 and r_2 sides	18.1	17.8
Line did not intersect compression wood areas on either r_1 or r_2 side	14.6	8.5
	100.0	100.0

Thus—with data on d.b.h. classes pooled—the line depicted in figure 9 (right) passed through a major area of compression wood on the r_1 side (or on both the r_1 and r_2 sides) in 79.9 percent of those sections with compression wood in *latifolia* and 86.4 percent of the *murrayana* sections that contained compression wood.

These proportions varied with d.b.h., however, as follows:

D.b.h.	Latifolia	Murrayana
mm	- - - - - - - Percent - - - - - - - -	
r_1 intersection (or both r_1 and r_2 intersections)		
76	86.8	94.1
152	85.4	83.1
228	68.8	80.0
Line did not intersect compression wood areas on either r_1 or r_2 side		
76	7.9	2.0
152	9.8	10.4
228	24.9	15.0

As noted previously, compression wood is extremely difficult to detect visually on exposed log ends under woods or mill conditions. Log sections that probably contain compression wood can be identified, however; see figures 19 and 20 with associated discussion. In such logs, a sawyer can predict that compression wood present will probably lie along the line depicted in figure 9b—and most likely be on the r_1 side. With this knowledge, the sawyer may be able to place the compression wood where it will be least damaging in the product he is manufacturing.

Variation Among Trees by D.b.h. Class and Latitude —*Murrayana*

Variety *murrayana* trees 76 mm in d.b.h. had significantly higher stem-average percentage of compression wood than those 152 mm or 228 mm in d.b.h. Compression-wood content was negatively correlated with d.b.h. as follows:

Tree d.b.h.	Number of trees	Compression wood content
mm		*Percent*
76	12	14.3
152	12	5.5
228	12	3.3
Average		7.7

With data from the 36 *murrayana* trees pooled, tree-average percentage of compression wood did not differ significantly with latitude, as follows:

Latitude	Compression wood content
Degrees	*Percent*
37.5	8.2
40	9.6
42.5	5.4
45	7.6

There were no significant interactions between d.b.h. and latitude. With data from all 36 trees pooled, the mean tree-average percentage of compression wood was 7.7 percent, with range from 0.1 to 26.2 percent. No tree of variety *murrayana* was found free of compression wood (table 7).

Variation of Compression Wood Content Within Stems—*Murrayana*

Percentage of compression wood content varied significantly with percent height in *murrayana* trees, the relationship differing with d.b.h. class (figs. 17 and 21; and table 6).

As noted under the discussion of variation of compression wood content within *latifolia* trees (and tabulation of correlation coefficients), stem sections or short logs

Table 7—Mean, standard deviation, and range in tree-average percentage compression wood in stems of *murrayana* by latitude, and tree d.b.h.[1]

Latitude	Tree d.b.h. 76 mm	152 mm	228 mm	All trees
Degrees	- - - - - - - - - - - - - - - - - Percent - - - - - - - - - - - - - - - - -			
37 5	16.97 (8.34)	5.10 (5.42)	2.40 (0.38)	8.16 (8.35)
	10.1-26.2	2.0-11.4	2.2-2.8	2.0-26.2
40	12.04 (7.79)	10.49 (2.20)	6.40 (2.26)	9.64 (4.90)
	4.1-19.7	8.3-12.7	4.5-8.9	4.1-19.7
42.5	10.87 (9.43)	3.88 (0.77)	1.41 (0.65)	5.38 (6.37)
	1.7-20.6	3.0-4.4	0.8-2.0	0.8-20.6
45	17.14 (10.01)	2.61 (1.22)	3.04 (4.66)	7.60 (9.06)
	6.1-25.5	1.4-3.8	0.1-8.4	0.1-25.5
Pooled	14.25 (8.17)	5.52 (4.05)	3.31 (2.97)	7.69 (7.20)
	1.7-26.2	1.4-12.7	0.1-8.9	0.1-26.2

[1]Entries in the table show the mean percentage, followed by the standard deviation in parentheses; listed below these two statistics is the range.

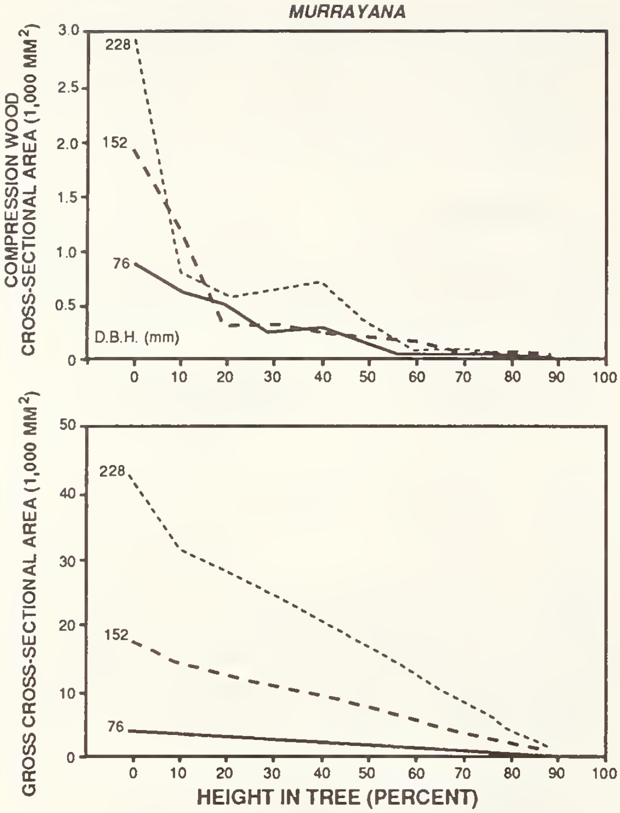


Figure 21—Variation with height in tree of compression wood cross-sectional area and gross cross-sectional area (bark-free) of *murrayana* trees of three diameters. See table 6 for numeric values.

sampled from *murrayana* trees will tend to contain a high percentage of compression wood if they are out of round and close to the ground, and have eccentric piths, high specific gravities, low moisture contents, and small minor diameters (figs. 19 and 20).

Location of Sections Free of Compression Wood—See previous discussion of pattern #4 occurrence under heading "Results—General Observations on Anatomy."

Location Within Section Where Compression Wood Will Probably Be Concentrated—See preceding discussion of *latifolia* under this same paragraph heading.

Compression Wood in *Latifolia* Compared to *Murrayana*

Variety *murrayana* (all 36 trees) averaged significantly more compression wood than variety *latifolia* (all 243 trees) with averages (tables 5, 6, and 7) as follows:

Tree d.b.h.	*Murrayana*	*Latifolia*
mm	- - - - - - *Percent* - - - - - -	
76	14.3	7.5
152	5.5	4.0
228	3.3	5.2
Average	7.7	5.5

Varietal differences in the proportions of trees in discrete compression-wood content classes were also significant (fig. 22).

When compared only at the latitudes (40, 42.5, and 45 degrees) and elevational zone (medium) the two samples had in common, tree-average percent compression wood was significantly greater in *murrayana* trees 76 mm and 152 mm in d.b.h. than in *latifolia* trees of these diameters, as follows:

Tree d.b.h.	*Murrayana*	*Latifolia*
mm	- - - - - - *Percent* - - - - - -	
76	13.4	6.3
152	5.7	2.2
228	3.6	6.3
Average	7.6	4.9

As noted previously, percentage of compression wood content in individual stem sections of *murrayana* was more strongly correlated with out-of-roundness, proximity to ground, pith eccentricity, wood specific gravity, wood moisture content, and disk diameter than was compression wood content in *latifolia*.

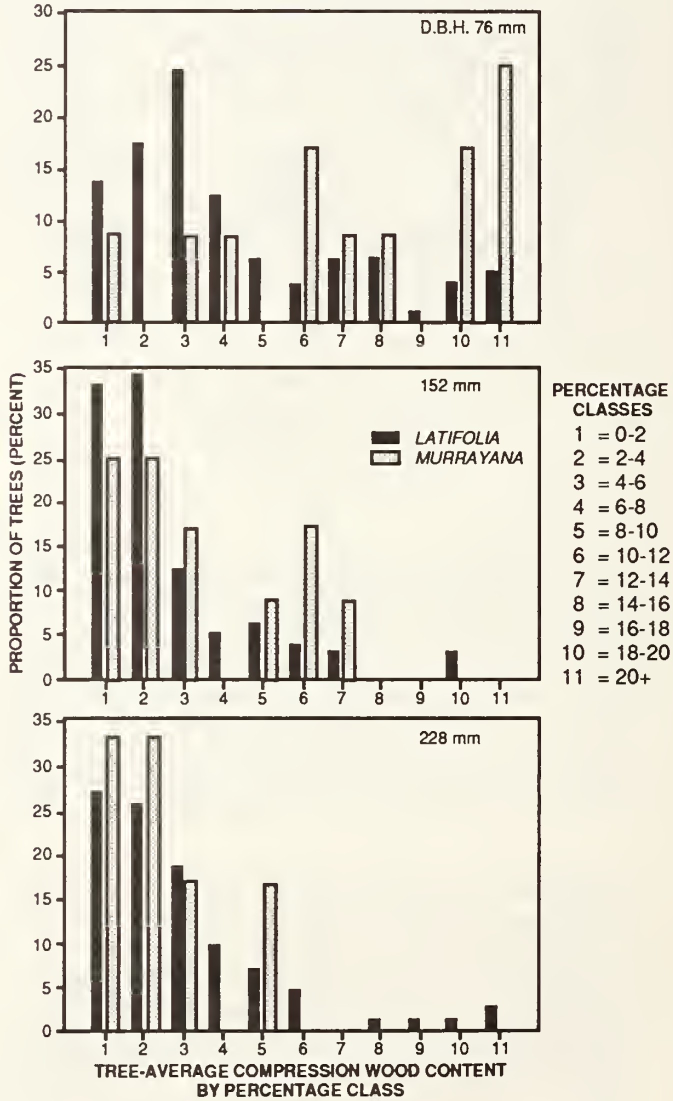


Figure 22—Frequency distribution of tree-average compression-wood content in *latifolia* and *murrayana* trees of three diameters. Data are based on 81 *latifolia* and 12 *murrayana* trees of each d.b.h.

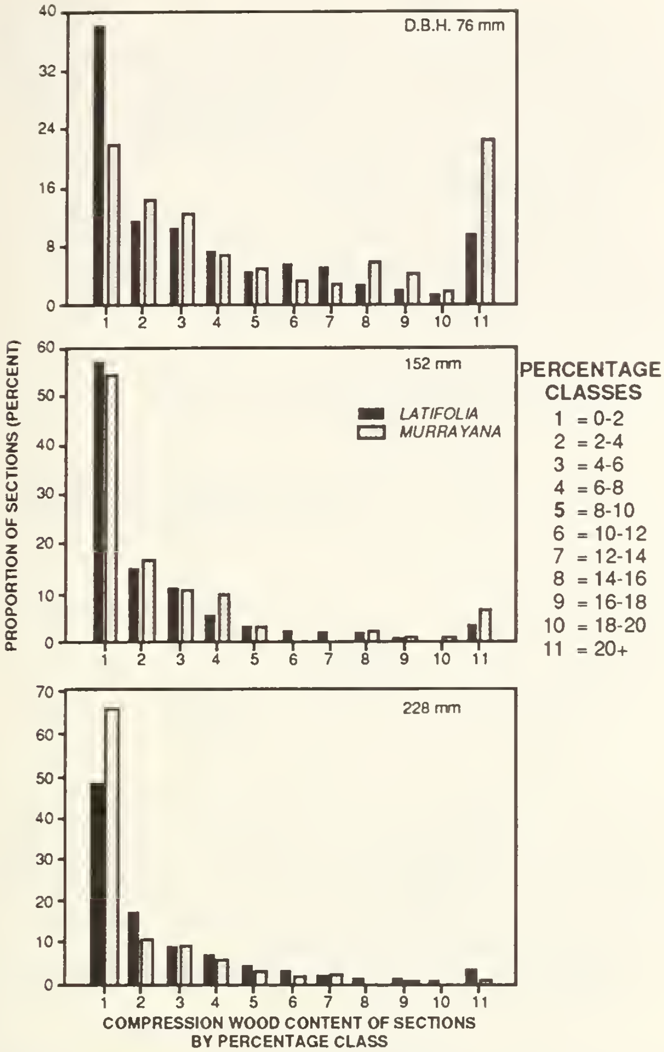


Figure 23—Frequency distribution of individual section's (disk's) compression-wood content in *latifolia* and *murrayana* trees of three diameters. Sections were taken at each tenth of tree height. Number of sections in each of the three d.b.h. classes was 810 for *latifolia* and 120 for *murrayana*.

With all sections of all trees from all latitudes considered, significant varietal differences by height were apparent (fig. 17), as were differences in the proportions of sections in discrete compression-wood content classes (fig. 23).

RESULTS—OUT-OF-ROUNDNESS INDEX

Geographic Variation and Variation Among Trees by D.b.h. Class and Elevational Class—*Latifolia*

Surprisingly, tree-average out-of-roundness index for bark-free stems (fig. 9) was not significantly correlated with tree-average compression-wood content. When individual sections taken at 10-percent height increments were considered, however, out-of-roundness index was negatively correlated with compression wood content as discussed in previous text; that is, tree stem sections that are out of round tend to have a high percentage of compression wood.

Additionally, stem out-of-roundness has considerable influence on optimum sawing patterns and lumber yield—and for this reason is now examined in detail.

The mean value (243 trees) for tree-average out-of-roundness index was 0.908. This value did not vary significantly with tree d.b.h. (table 8) or with elevational zone. It did, however vary significantly with latitude, as follows:

Latitude	Out-of-roundness index
Degrees	
40	0.911
42.5	.912
45	.917
47.5	.905
50	.914
52.5	.903
55	.916
57.5	.897
60	.895

Table 8—Comparison by d.b.h. class of measures of tree-average out-of-roundness and pith eccentricity between varieties *latifolia* and *murrayana*, with data from all latitudes pooled, and with data pooled only from those latitudes and the elevational class common to the two varieties (see figure 9 for definitions)

Tree d.b.h., mm	Out-of-roundness index		e		e/r^1		r_1/r_2	
	Latifolia	*Murrayana*	*Latifolia*	*Murrayana*	*Latifolia*	*Murrayana*	*Latifolia*	*Murrayana*
All latitudes								
76	0.907	0.901	3.3	3.9	0.10	0.12	1.30	1.36
152	.908	.913	6.2	6.5	.10	.10	1.28	1.31
228	.909	.910	10.4	9.7	.11	.10	1.31	1.29
Average	.908	.908	6.6	6.7	.11	.11	1.30	1.32
Latitude 40, 42.5, and 45 degrees								
76	0.912	0.901	2.8	3.8	0.10	0.11	1.24	1.35
152	.918	.910	5.4	6.1	.09	.09	1.24	1.29
228	.910	.917	9.2	10.3	.11	.11	1.30	1.30
Average	.913	.909	5.8	6.7	.10	.10	1.26	1.31

These data suggest that tree stems are most nearly circular in average cross section in those latitudinal zones from 40 degrees to 55 degrees (with the exception of zones at 47.5 degrees and 52.5 degrees), and are more elliptical in the northernmost zones of 57.5 and 60 degrees.

There were no significant interactions among the three factors: d.b.h., elevational zone, and latitude.

As noted previously, the 243-tree average was 0.908; standard deviation was 0.02, with range in out-of-roundness index from 0.82 to 0.94. This range suggests that although tree stems may have nearly circular cross sections at some level above ground, tree-average sections are considerably out of round.

Identification of Trees That Will Have Out-of-Round Stems—*Latifolia*

Although tree-average out-of-roundness index was not significantly related to tree d.b.h. or elevational zone, it was significantly correlated (0.05 level) with many other tree characteristics, as follows:

Sign of correlation and tree characteristic	r
Positive	
Stemwood moisture content	0.267
Moisture content of complete tree	.262
Moisture content of sapwood	.214
Elevation, feet	.181
Number of live branches	.167
Stembark moisture content	.153
Average annual ring width at stump top	.137
Negative	
r_1/r_2 (fig. 9)	–0.335
Latitude (degrees)	–.234
Longitude (degrees)	–.198
Stembark specific gravity	–.197
Stemwood specific gravity	–.189
e (fig. 9)	–.166
Average live branch angle (degrees)	–.147
e/r_1 (fig. 9)	–.131
Tree age at stump (years)	–.154
Bark percentage of complete-tree ovendry weight	–.140
Maximum stem crook	–.132

These correlations suggest that in addition to the latitude relationships previously noted (and the longitude correlation because of the longitudinal skew of the sample zones as shown in figure 1), entire stems of *latifolia* are likely to average most circular in cross section in fast-growing young trees of high moisture content, low specific gravity, with pith not eccentric, little stem crook, low bark percentage of complete-tree ovendry weight, and with many live branches making a small angle with the stem above them. Because latitude is inversely correlated with meters of elevation, trees at higher elevations may have stems more nearly circular in cross section than those at lowest elevations.

Variation Within Tree Stems—*Latifolia*

Out-of-roundness index varied significantly with percent height in *latifolia* trees, the relationship differing by d.b.h. class (table 6). With all data pooled, it appears that in both varieties, stems are most nearly circular in cross section near midheight (fig. 24).

When out-of-roundness index of each of the 2,430 (243 trees x 10 heights) *latifolia* sections was correlated—and each of the 360 *murrayana* sections similarly correlated—with each section's other properties, some significant relationships were evident, as follows:

Section's characteristic correlated with the section's out-of-roundness index	***Latifolia*** **(n = 2,430)** r	***Murrayana*** **(n = 360)** r
Positive correlations		
Minor diameter	0.084	N.S.
Moisture content of wood	.059	0.110
Negative correlations		
r_1/r_2 (fig. 25)	–0.274	–0.283
e/r_1 (fig. 25)	–.256	–.218
Percentage compression wood content	–.180	–.188
Specific gravity of wood	–.178	–.209
Pith eccentricity, e	–.173	–.201

These correlations suggest that sections (or short logs) sampled in *latifolia* stems will tend to be out of round if they contain much compression wood or have eccentric piths, high specific gravity, small minor diameter, and low moisture content; the last two relationships, although statistically significant, are weak.

Out-of-roundness index was not significantly correlated with height above ground.

Variation Among Trees by D.b.h. Class and Latitude—*Murrayana*

Variety *murrayana* bark-free stems had tree-average out-of-roundness index of 0.91, with standard deviation of 0.03 and range from 0.81 to 0.94. Values did not differ significantly with latitude or diameter class; there was no significant latitude x diameter interaction. Averages by diameter class are summarized as follows:

D.b.h.	n	**Mean**	**Standard deviation**	**Range**
mm				
76	12	0.901	0.033	0.81-0.94
152	12	.913	.023	.86-.94
228	12	.910	.024	.84-.93

With data for trees of all three diameters pooled, tree-average values by latitude were as follows:

Latitude	n	**Mean**	**Standard deviation**	**Range**
Degrees				
37.5	9	0.903	0.027	0.84-0.92
40	9	.903	.037	.81-.93
42.5	9	.911	.026	.86-.94
45	9	.913	.015	.89-.94

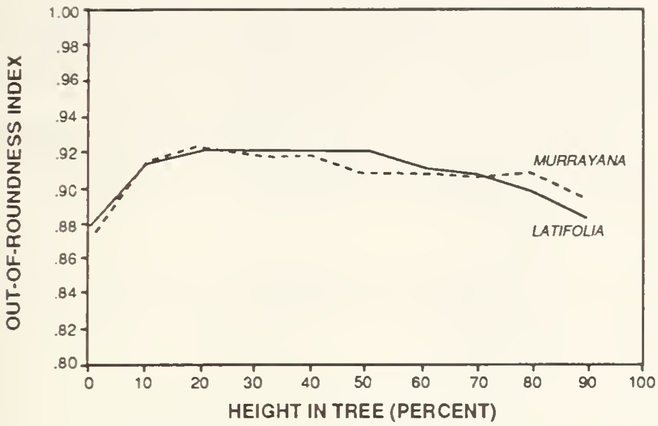


Figure 24—Variation in out-of-roundness index (bark-free) with height in trees of *latifolia* (243 trees) and *murrayana* (36 trees); all data pooled.

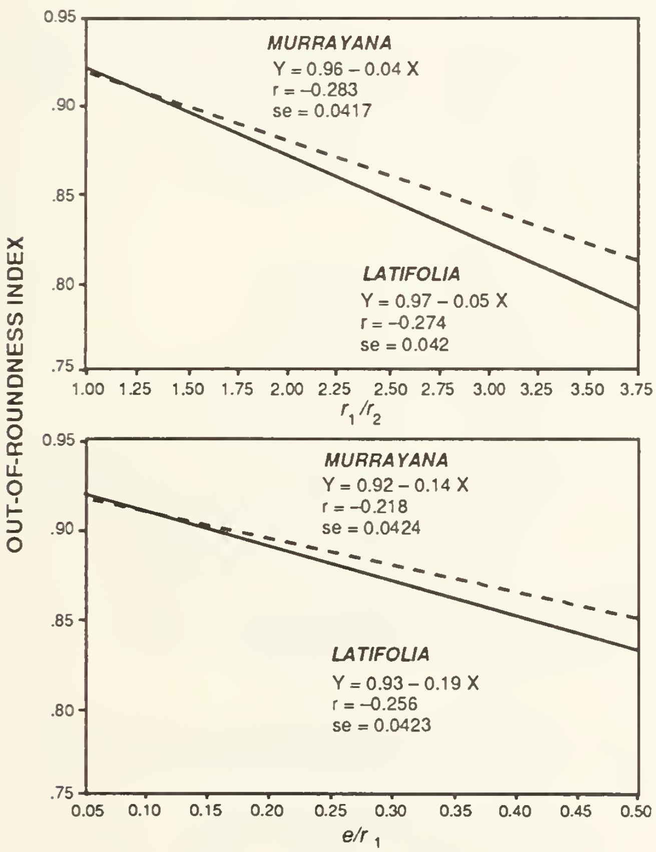


Figure 25—Regression equations relating out-of-roundness index of individual stem sections of *latifolia* (n = 2,430) and *murrayana* (n = 360) to two measures of pith eccentricity (e/r_1 and r_1/r_2).

Variation Within Tree Stems—*Murrayana*

Out-of-roundness varied significantly with percent height in *murrayana* trees (fig. 24), the relationship differing by d.b.h. class (table 6).

As noted under the discussion of variation of out-of-roundness index within *latifolia* trees (and tabulation of correlation coefficients), stem sections or short logs sampled from *murrayana* stems will tend to be out of round if they contain much compression wood or have eccentric piths, high specific gravity, and low moisture content.

Out-of-Roundness Index of *Latifolia* Compared to *Murrayana*

Tree-average out-of-roundness index did not differ significantly between *murrayana* and *latifolia* (fig. 24); see table 8 for average values. This was true for all-latitude comparisons as well as comparisons at the latitudes and elevations sampled in common.

With all sections of all trees from all latitudes considered, however, significant varietal differences in the proportions of sections in discrete out-of-roundness classes were apparent (fig. 26).

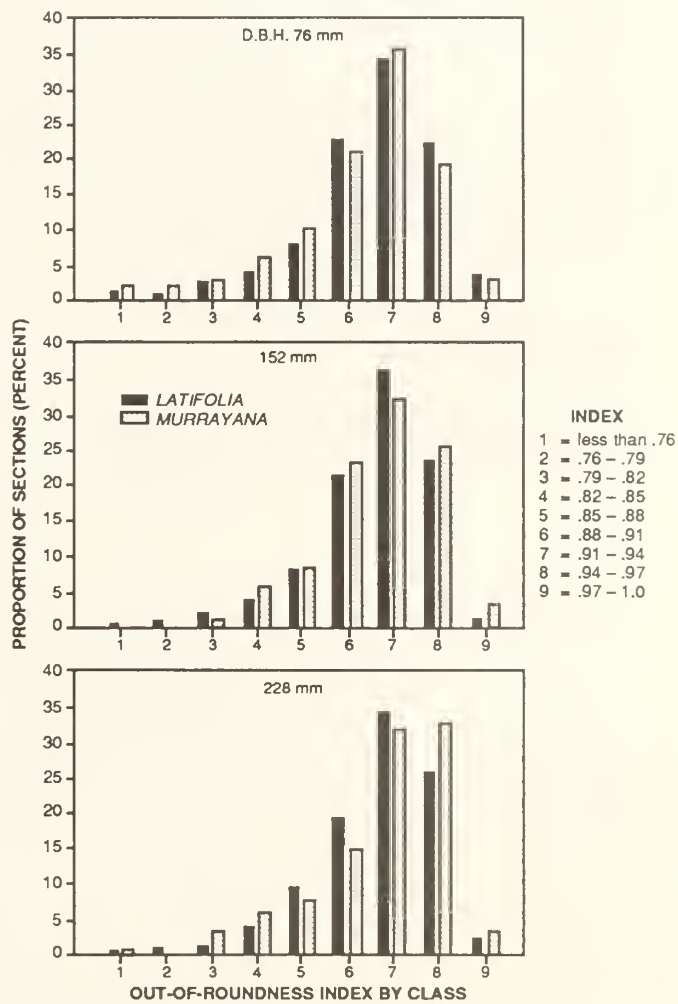


Figure 26—Frequency distribution of individual section's (disk's) out-of-roundness index in *latifolia* and *murrayana* trees of three diameters. Sections were taken at each tenth of tree height. Number of sections in each of the three d.b.h. classes was 810 for *latifolia* and 120 for *murrayana*.

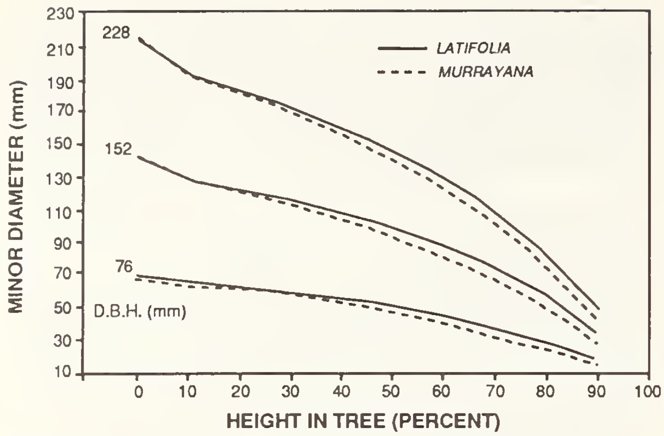


Figure 27—Variation with height in tree of minor diameter (fig. 9) of bark-free stems of *latifolia* and *murrayana* trees of three diameters. See table 6 for numeric values.

Minor Diameters of *Latifolia* Compared to *Murrayana*—Bark-Free

Minor-diameter variation with height in tree (table 6) is important to manufacturers of roundwood products—particularly dowelled products. Minor diameter is related to both stem taper and out-of-roundness. In trees of comparable d.b.h., and at comparable percentages of tree height, upper *murrayana* stems have slightly smaller minor diameters than *latifolia* stems (fig. 27).

RESULTS—MEASURES OF PITH ECCENTRICITY

Three characteristics that provide a measure of pith eccentricity seem useful: e, e/r_1, and r_1/r_2, as defined in figure 9. Following is a discussion of these characteristics by variety.

Latifolia—e

Geographic Variation and Variation Among Trees by D.b.h. Class and Elevational Class—With data from all 243 trees pooled, tree-average pith eccentricity (e) averaged 6.63 mm, with standard deviation of 3.92 mm and range from 0.50 mm to 25.0 mm. Large trees had significantly greater average pith eccentricity than small trees (fig. 28), with no significant d.b.h. interactions with latitude or elevational zone, as follows:

D.b.h.	Mean	Standard deviation	Range
		mm	
76	3.3	1.3	0.5-7.6
152	6.2	2.1	2.3-10.4
228	10.4	3.8	4.6-25.0

Pith eccentricity averaged least in the medium elevational zone (6.2 mm) and was greater at low elevation (6.6 mm) and at high elevation (7.1 mm). At latitudes 42.5, 52.5, and 57.5 degrees, however, low-zone trees had less pith eccentricity than medium (table 9).

Pith eccentricity averaged less (5.5-6.3 mm) in intermediate latitudinal zones of 45 to 52.5 degrees than in more southerly and more northerly latitudes (6.8-8.0 mm). See table 9.

The variation with d.b.h., latitude, and elevational zone seems sufficient to tabulate pith eccentricty (e) partitioned by these factors (table 10).

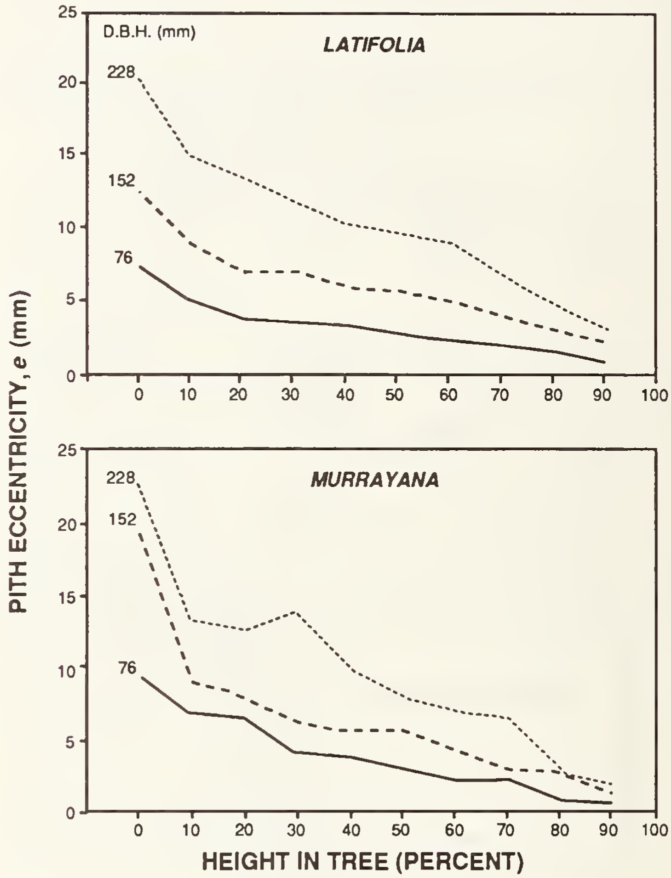


Figure 28—Variation of pith eccentricity (e) with height in stems of *latifolia* (81 of each d.b.h.) and *murrayana* (12 of each d.b.h.) trees of three diameters.

Table 9—Variation of tree-average pith eccentricity (e) in *latifolia* related to latitude and elevational zone.

Latitude	Elevational zone Low	Medium	High	Average
Degrees		*mm*		
40	8.7	6.1	6.4	7.1
42.5	6.1	6.7	7.8	6.9
45	6.0	4.6	5.9	5.5
47.5	6.0	5.5	6.5	6.0
50	6.0	4.9	7.5	6.1
52.5	4.5	6.9	7.6	6.3
55	7.5	6.4	6.6	6.8
57.5	5.9	7.4	7.9	7.1
60	8.6	7.8	7.7	8.0
Average	6.6	6.2	7.1	6.6

Table 10—Mean, standard deviation, and range in tree-average pith eccentricity (*e*) in stems of *latifolia* by latitude, elevational class, and tree d.b.h.[1]

Elevational class	Tree d.b.h. 76 mm	152 mm	228 mm	All trees
	Millimeters			
		40° Latitude		
Low	3.77 (1.92)	9.17 (1.33)	13.17 (1.37)	8.70 (4.30)
	1.7-5.5	7.7-10.3	11.6-14.1	1.7-14.1
Medium	3.33 (1.14)	4.87 (0.55)	10.23 (0.64)	6.14 (3.22)
	2.4-4.6	4.3-5.4	9.5-10.6	2.4-10.6
High	2.50 (0.17)	6.13 (2.28)	10.67 (0.55)	6.43 (3.73)
	2.3-2.6	4.1-8.6	10.3-11.3	2.3-11.3
		42.5° Latitude		
Low	3.20 (1.28)	7.63 (1.76)	7.37 (1.91)	6.07 (2.59)
	2.1-4.6	5.8-9.3	5.6-9.4	2.1-9.4
Medium	2.47 (0.83)	6.17 (3.84)	11.47 (2.11)	6.70 (4.51)
	1.8-3.4	2.9-10.4	10.2-13.9	1.8-13.9
High	2.63 (0.75)	5.10 (1.13)	15.70 (8.54)	7.81 (7.41)
	1.9-3.4	3.8-5.8	8.2-25.0	1.9-25.0
		45° Latitude		
Low	4.03 (0.91)	7.10 (1.47)	6.73 (2.25)	5.96 (2.03)
	3.2-5.0	5.8-8.7	4.8-9.2	3.2-9.2
Medium	2.53 (0.67)	5.23 (2.04)	5.90 (1.35)	4.56 (2.00)
	2.1-3.3	2.9-6.7	4.8-7.4	2.1-7.4
High	3.53 (0.47)	3.67 (1.34)	10.47 (5.51)	5.89 (4.46)
	3.0-3.9	2.7-5.2	6.8-16.8	2.7-16.8
		47.5° Latitude		
Low	1.87 (0.40)	5.37 (2.32)	10.80 (3.90)	6.01 (4.52)
	1.4-2.1	2.9-7.5	6.8-14.6	1.4-14.6
Medium	3.23 (1.37)	5.37 (1.10)	7.83 (4.65)	5.48 (3.19)
	2.3-4.8	4.1-6.1	5.0-13.2	2.3-13.2
High	4.37 (1.71)	6.17 (3.59)	9.07 (3.80)	6.53 (3.43)
	2.4-5.5	3.9-10.3	5.3-12.9	2.4-12.9
		50° Latitude		
Low	2.47 (0.59)	5.57 (1.54)	10.00 (3.25)	6.01 (3.75)
	1.8-2.9	3.8-6.6	7.6-13.7	1.8-13.7
Medium	2.00 (0.82)	5.03 (2.70)	6.43 (0.40)	4.89 (2.43)
	1.3-2.9	2.3-7.7	6.0-6.8	1.3-7.7
High	2.80 (0.44)	4.83 (0.72)	14.93 (3.86)	7.52 (5.96)
	2.3-3.1	4.0-5.3	11.2-18.9	2.3-18.9
		52.5° Latitude		
Low	2.70 (0.92)	4.17 (0.57)	6.50 (1.68)	4.46 (1.94)
	1.9-3.7	3.7-4.8	4.6-7.8	1.9-7.8
Medium	3.37 (0.35)	7.00 (1.37)	10.27 (0.67)	6.88 (3.09)
	3.0-3.7	5.5-8.2	9.5-10.7	3.0-10.7
High	5.70 (1.68)	6.63 (1.72)	10.50 (2.86)	7.61 (2.89)
	4.4-7.6	4.7-8.0	7.2-12.2	4.4-12.2
		55° Latitude		
Low	2.67 (0.60)	8.23 (1.01)	11.67 (2.72)	7.52 (4.20)
	2.1-3.3	7.3-9.3	8.6-13.8	2.1-13.8
Medium	3.63 (1.18)	5.27 (2.10)	10.23 (1.86)	6.38 (3.34)
	2.9-5.0	3.1-7.3	8.1-11.5	2.9-11.5
High	3.93 (1.31)	7.83 (1.86)	7.93 (2.20)	6.57 (2.53)
	2.7-5.3	6.3-9.9	5.4-9.3	2.7-9.9
		57.5° Latitude		
Low	2.40 (1.71)	4.50 (0.75)	10.90 (4.71)	5.93 (4.60)
	0.5-3.8	3.7-5.2	7.2-16.2	0.5-16.2
Medium	3.10 (1.51)	7.93 (2.25)	11.10 (3.93)	7.38 (4.23)
	1.7-4.7	5.4-9.7	6.8-14.5	1.7-14.5
High	4.00 (0.61)	7.10 (1.91)	12.47 (3.18)	7.86 (4.16)
	3.6-4.7	5.9-9.3	8.9-15.0	3.6-15.0

(con.)

Table 10—(Con.)

Elevational class	Tree d.b.h. 76 mm	152 mm	228 mm	All trees
	- - - - - -	- - - Millimeters	- - - - - -	- - - - - -
		60° Latitude		
Low	5.77 (1.50) 4.1-7.0	7.20 (2.94) 3.8-8.9	12.77 (2.11) 11.0-15.1	8.58 (3.75) 3.8-15.1
Medium	3.37 (0.76) 2.5-3.9	7.17 (2.40) 5.4-9.9	12.87 (4.93) 7.2-16.2	7.80 (4.98) 2.5-16.2
High	3.37 (0.12) 3.3-3.5	6.57 (1.72) 4.6-7.8	13.17 (3.35) 9.3-15.2	7.70 (4.72) 3.3-15.2
		Pooled		
Low	3.29 (1.29) 0.5-7.6	6.19 (2.11) 2.3-10.4	10.41 (3.78) 4.6-25.0	6.63 (3.92) 0.5-25.0

[1]Entries in the table show the mean value, followed by the standard deviation in parentheses; listed below these two statistics is the range.

Identification of *Latifolia* Trees That Will Have Eccentric Piths—Tree-average pith eccentricity (*e*) was not only significantly related to geographic location, elevational zone, and d.b.h., but was also significantly correlated (0.05 level) with many other tree characteristics, as follows:

Sign of correlation and tree characteristic	*r*
Positive	
D.b.h.	0.743
Diameter at 152-mm-high stump top	.739
Total stump-root weight including bark, ovendry	.698
Complete-tree weight, ovendry	.697
Heartwood diameter at 152-mm-high stump top	.696
Total stem weight including bark, ovendry	.674
Total stemwood weight, ovendry	.670
Average live branch diameter	.657
Foliage weight, ovendry	.647
Stem diameter at base of live crown	.639
Sapwood weight, ovendry	.634
Live branch weight with bark, ovendry	.612
Heartwood weight	.597
Width of live crown	.580
Tree height to apical tip	.555
Total number of cones on first foot of top 25 branches	.553
Stem taper within live crown, millimeters per meter	.550
Age at stump top	.530
Branch bark thickness	.463
Average bark thickness of stump	.439
Number of live branches	.395
Stem taper from stump top to base of live crown, millimeters per meter	.394
Stembark thickness at top of 152-mm-high stump	.392
Taproot length	.381
Dead branch weight, ovendry	.375
Number of dead branches	.371
Length of live crown	.327
Branchwood proportion of ovendry complete-tree weight	.272
Stembark specific gravity	.260
Average ring width at 152-mm-high stump top	.259
Cone weight proportion of complete-tree ovendry weight	.216
Moisture content of sapwood, percent of ovendry weight	.206
Stemwood proportion of ovendry complete-tree weight	.167
Maximum stem crook	.142
Negative	
Tree bark proportion of ovendry complete-tree weight	–0.428
Stembark moisture content, percent of ovendry weight	–.381
Stump-root wood proportion of ovendry complete-tree weight	–.346
Moisture content of heartwood, percent of ovendry weight	–.289
Stemwood specific gravity	–.188
Foliage proportion of ovendry complete-tree weight	–.188
Tree-average out-of-roundness index	–.166
Crown ratio	–.133
Moisture content of complete tree, percent of ovendry weight	–.131

These correlation coefficients indicate that tree-average pith eccentricity (*e*) is greatest in fast-growing, large-diameter, tall trees with sapwood of low moisture content. Surprisingly, stem crook was not a strongly related factor ($r = +0.142$). The negative correlation coefficients suggest that tree-average pith eccentricity is least in trees of high moisture content in heartwood and stembark, and high tree-average out-of-roundness index (those most circular in cross section).

Variation of Pith Eccentricity (*e*) Within *Latifolia* Trees—Pith eccentricity varied significantly with percent height in *latifolia* trees, the relationship differing by d.b.h. class (fig. 28 and table 6).

When pith eccentricity of each of the 2,430 (243 trees x 10 heights) *latifolia* sections was correlated—and each of the 360 *murrayana* sections similarly correlated—with other properties of each section, some significant relationships were evident, as follows:

Section's characteristic correlated with the section's pith eccentricity (*e*)	*Latifolia* (*n* = 2,430) *r*	*Murrayana* (*n* = 360) *r*
Positive correlations		
e/r_1	0.712	0.725
Major diameter (fig. 29)	.637	.699
r_1/r_2	.623	.779
Percentage compression wood (fig. 29)	.187	.230
Wood specific gravity	.123	N.S.
Negative correlations		
Height above ground, meters (fig. 30)	–0.287	–0.307
Moisture content of wood (fig. 30)	–.248	–.213
Out-of-roundness index	–.173	–.201

These correlations suggest that a section (or short log) sampled in a *latifolia* stem will tend to have large pith eccentricity if it is large in diameter, out of round, and in the lower stem portion, and if it has large compression wood content, high specific gravity, and low moisture content.

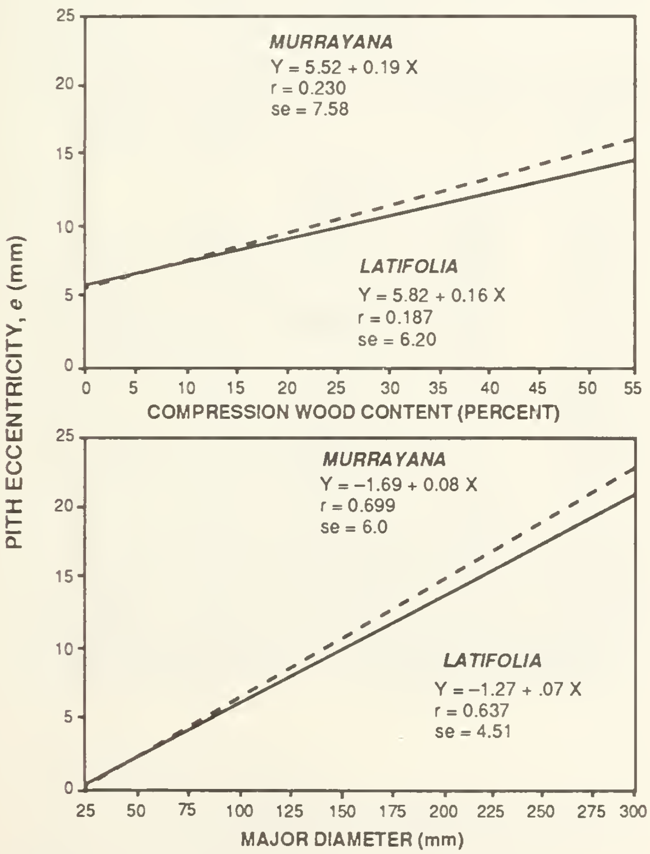


Figure 29—Regression equations relating pith eccentricity (*e*) of individual stem sections of *latifolia* and *murrayana* trees to compression wood content and major diameter of the sections. The equations are based on 2,430 and 360 sections, respectively.

Murrayana—e

Among *Murrayana* Trees—Pith eccentricity (*e*) in *murrayana* averaged 6.70 mm, with standard deviation of 3.75 mm and range from 2.0 mm to 15.7 mm (table 11). This eccentricity did not vary significantly with latitude, but was positively correlated with d.b.h., as follows:

D.b.h.	*e*
- - - - - - - *mm* - - - - - -	
76	3.9
152	6.5
228	9.7

Within *murrayana* Trees—Pith eccentricity (*e*) varied significantly with percent height in *murrayana* trees, the relationship differing by d.b.h. class (fig. 28 and table 6).

As noted under the discussion of pith eccentricity within *latifolia* trees—and accompanying tabulation of correlation coefficients—a stem section (or short log) sampled from a *murrayana* tree will tend to have large pith eccentricity if it is large in diameter, out of round, and in the lower stem portion, and if it has a large compression wood content and low moisture content (figs. 29 and 30).

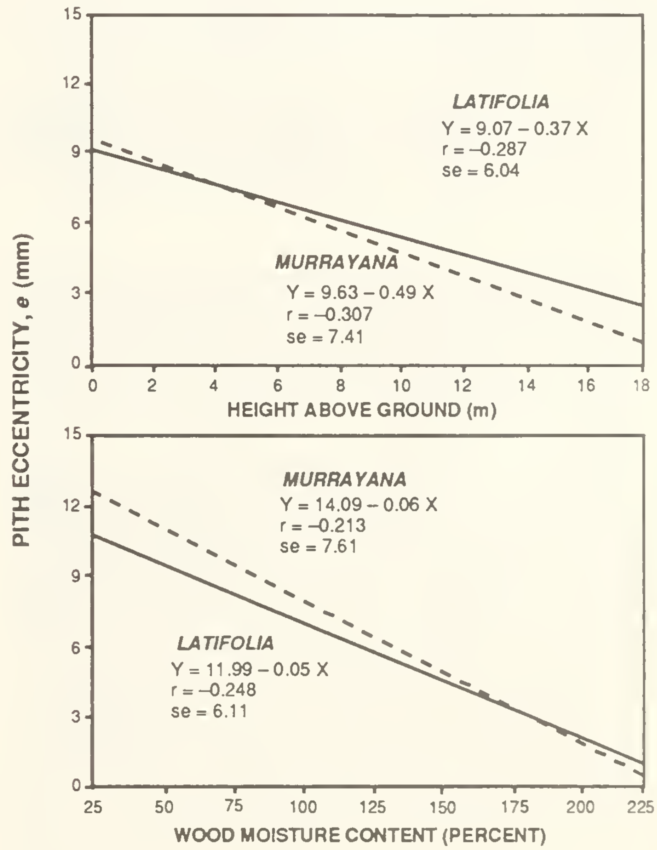


Figure 30—Regression equations relating pith eccentricity (*e*) of individual stem sections of *latifolia* and *murrayana* trees to wood moisture content and height above ground of each section. The equations are based on 2,430 and 360 sections, respectively.

Table 11—Mean, standard deviation, and range in tree-average pith eccentricity (*e*) in stems of *murrayana* by latitude and tree d.b.h.[1]

Latitude	Tree d.b.h. 76 mm	152 mm	228 mm	All trees
Degrees	*Millimeters*			
37.5	4.00 (1.65)	7.50 (2.01)	8.00 (2.62)	6.50 (2.64)
	2.9-5.9	5.2-8.9	5.6-10.8	2.9-10.8
40	5.13 (2.56)	7.37 (2.76)	10.23 (4.75)	7.58 (3.75)
	2.2-6.9	5.3-10.5	7.1-15.7	2.2-15.7
42.5	3.23 (0.75)	8.00 (0.95)	11.70 (4.80)	7.64 (4.43)
	2.8-4.1	7.4-9.1	6.3-15.5	2.8-15.5
45	3.17 (1.39)	3.07 (0.59)	9.03 (5.17)	5.09 (4.00)
	2.0-4.7	2.4-3.5	5.8-15.0	2.0-15.0
Pooled	3.88 (1.68)	6.48 (2.58)	9.74 (4.06)	6.70 (3.75)
	2.0-6.9	2.4-10.5	5.6-15.7	2.0-15.7

[1]Entries in the table show the mean value, followed by the standard deviation in parentheses; listed below these two statistics is the range.

Pith Eccentricity (*e*) of *Latifolia* Compared to That of *Murrayana*

No significant differences between the two varieties were found in tree-average pith eccentricity (*e*); see table 8. As noted previously, pith eccentricity in individual stem sections of *murrayana* was more strongly correlated with section diameter, out-of-roundness, height above ground, and percentage compression wood (but not wood moisture content and specific gravity) than pith eccentricity in *latifolia* was correlated with these characteristics in individual stem sections (figs. 29 and 30).

Latifolia—e/r_1

A high value of the ratio e/r_1 indicates a high degree of pith eccentricity and out-of-roundness (fig. 9). Of all the factors evaluated, the ratio e/r_1 was best correlated with percentage of compression wood in individual sections (fig. 19).

Geographic Variation and Variation Among D.b.h. Classes and Elevational Classes—Tree-average values for the ratio e/r_1 averaged 0.11 for *latifolia*, with standard deviation of 0.03 and range from 0.02 to 0.22. Trees 152 mm in d.b.h. did not vary significantly with either latitude or elevational class (average 0.11). Trees 76 mm and 228 mm in d.b.h. did vary significantly, however, in an elevational class x latitude interaction (table 12). These data suggest that trees with lowest ratios will be found at medium elevation from latitude 45 degrees through 50 degrees, or at low elevation from 47.5 degrees through 52.5 degrees.

Table 12—Tree-average means for *latifolia* of ratio e/r_1 related to latitude, d.b.h., and elevational class

D.b.h.	Elevational class Low	Medium	High	Averages
mm				
		40° Latitude		
76	0.13	0.11	0.09	0.11
152	.15	.09	.10	.11
228	.13	.12	.11	.12
All				.11
		42.5° Latitude		
76	.10	.09	.09	.09
152	.12	.10	.09	.10
228	.09	.13	.15	.12
All				.10
		45° Latitude		
76	.12	.09	.10	.10
152	.11	.09	.06	.09
228	.09	.07	.12	.09
All				.09
		47.5° Latitude		
76	.07	.10	.13	.10
152	.09	.09	.10	.09
228	.11	.09	.10	.10
All				.10
		50° Latitude		
76	.09	.07	.09	.08
152	.10	.08	.09	.09
228	.11	.07	.16	.11
All				.09
		52.5° Latitude		
76	.09	.10	.17	.12
152	.08	.11	.11	.10
228	.08	.12	.12	.11
All				.11
		55° Latitude		
76	.08	.12	.12	.11
152	.13	.09	.12	.11
228	.13	.12	.09	.11
All				.11
		57.5° Latitude		
76	.08	.09	.12	.10
152	.08	.11	.11	.10
228	.13	.12	.13	.13
All				.11
		60° Latitude		
76	.17	.11	.12	.13
152	.12	.12	.11	.12
228	.13	.13	.13	.13
All				.13
Average[1]	0.11	0.10	0.11	0.11

[1]By diameter the averages are: 76 mm (0.10); 152 mm (0.10); 228 mm (0.11).

Identification of Trees That Will Have Low Average e/r_1 Ratios—In addition to the significant interaction: elevational class x latitude, the tree-average e/r_1 ratio was significantly (0.05 level) correlated with a few tree characteristics, as follows:

Sign of correlation and tree characteristic	r
Positive	
r_1/r_2 (fig. 9)	0.929
e (fig. 9)	.673
Percentage of compression wood	.336
Age at stump	.148
Elevation, meters	.130
Negative	
Out-of-roundness index (fig. 9)	−0.296
Average ring width at 152-mm-high stump	−.141
Moisture content of complete tree	−.126

In addition to suggesting that low e/r_1 ratios are found in stems with circular cross section and centered pith, low ratios will be found at low elevation in fast-growing young trees with high complete-tree moisture content.

Variation of e/r_1 Within *Latifolia* Trees—The ratio e/r_1 varied significantly with height in *latifolia* trees, the relationship differing with d.b.h. class (fig. 31 and table 6). When this ratio of each of the 2,430 (243 trees x 10 heights) *latifolia* sections was correlated—and each of the 360 *murrayana* sections similarly correleated—with other properties of each section, some significant relationships were evident, as follows:

Section's characteristic correlated with the section's e/r_1 ratio	*Latifolia* (n = 2,430) r	*Murrayana* (n = 360) r
Positive		
r_1/r_2	0.851	0.884
e	.712	.725
Percentage compression wood (fig. 19)	.362	.489
Wood specific gravity	.185	.270
Major diameter	.164	.180
Negative		
Out-of-roundness index (fig. 25)	−0.256	−0.218
Wood moisture content	−.146	−.324
Height above ground, meters	−.141	−.324

Obviously those sections that are cylindrical with centered piths will have small e/r_1 ratios. Additionally, small ratios will tend to be found in high-above-ground sections of large diameter, low specific gravity, and high moisture content; and in sections with low percentage of compression wood (fig. 19).

Murrayana—e/r_1

The mean tree-average ratio e/r_1 for *murrayana* trees was 0.11, with standard deviation of 0.04 and range from 0.05 to 0.18 . The ratio did not vary significantly with either latitude or d.b.h. class.

As noted under the discussion of variation of this ratio within *latifolia* trees (and the tabulation of correlation

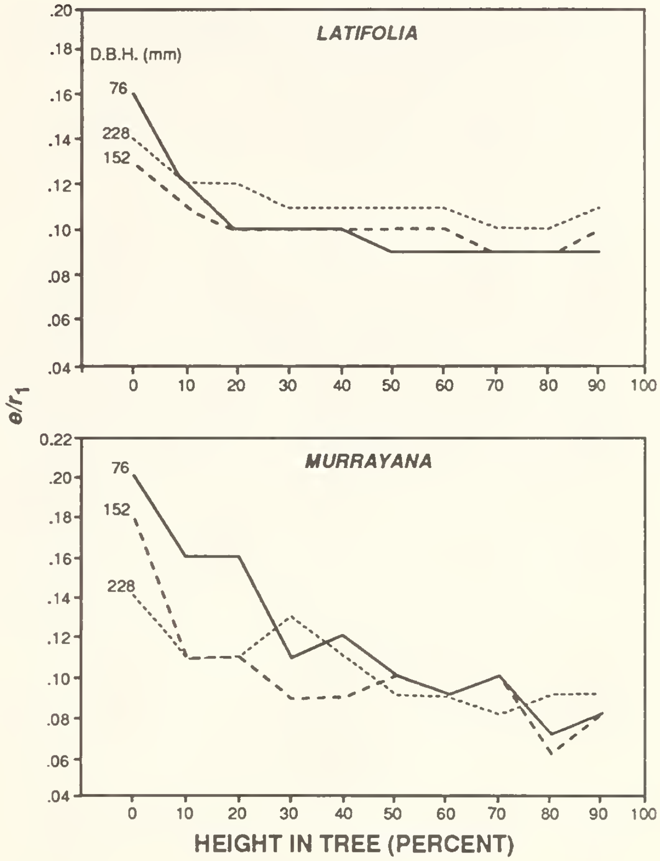


Figure 31—Variation of ratio e/r_1 with height in stems of *latifolia* (81 of each d.b.h.) and *murrayana* (12 of each d.b.h.) trees of three diameters.

coefficients), stem sections or short logs sampled from *murrayana* trees will also tend to have low ratios in high-above-ground sections of large diameter, low specific gravity, and high moisture content; and in sections with low percentage of compression wood (figs. 19 and 31).

e/r_1 of *Latifolia* Compared to *Murrayana*

All latitudes considered, or in the latitudes the two varieties were sampled in common, this ratio did not differ significantly between *murrayana* and *latifolia*. See table 6 and figures 19 and 31 for comparative values.

Latifolia—r_1/r_2

A high value for the ratio r_1/r_2 (fig. 9) indicates a high degree of pith eccentricity; a low value indicates concentricity. The ratio is positively correlated with percentage of compression wood (fig. 19).

Geographic Variation and Variation Among D.b.h. Classes and Elevational Classes—Tree-average values for the ratio r_1/r_2 averaged 1.30 with standard deviation of 0.12 and range from 1.08 to 1.82. These tree-average values differed significantly in a three-way interaction:

Table 13—Tree-average means for *latifolia* of ratio r_1/r_2 related to latitude, d.b.h., and elevational class

D.b.h.	Elevational class Low	Medium	High	Averages
mm				
		40° Latitude		
76	1.32	1.27	1.19	1.26
152	1.43	1.22	1.32	1.32
228	1.37	1.34	1.34	1.35
All				1.31
		42.5° Latitude		
76	1.29	1.22	1.26	1.26
152	1.36	1.28	1.21	1.28
228	1.19	1.37	1.45	1.34
All				1.29
		45° Latitude		
76	1.38	1.24	1.29	1.30
152	1.29	1.23	1.18	1.23
228	1.19	1.19	1.38	1.25
All				1.26
		47.5° Latitude		
76	1.19	1.30	1.44	1.31
152	1.26	1.22	1.28	1.25
228	1.25	1.19	1.27	1.24
All				1.27
		50° Latitude		
76	1.21	1.18	1.23	1.21
152	1.23	1.21	1.22	1.22
228	1.29	1.15	1.47	1.30
All				1.24
		52.5° Latitude		
76	1.22	1.25	1.57	1.35
152	1.21	1.33	1.29	1.28
228	1.21	1.29	1.33	1.28
All				1.30
		55° Latitude		
76	1.28	1.33	1.36	1.32
152	1.40	1.22	1.35	1.32
228	1.33	1.31	1.20	1.28
All				1.31
		57.5° Latitude		
76	1.29	1.30	1.39	1.33
152	1.18	1.36	1.32	1.29
228	1.30	1.31	1.39	1.33
All				1.31
		60° Latitude		
76	1.58	1.29	1.31	1.39
152	1.32	1.39	1.31	1.34
228	1.36	1.38	1.41	1.38
All				1.37
Average[1]	1.29	1.27	1.32	1.30

[1]By diameter the averages are: 76 mm (1.30); 152 mm (1.28); 228 mm (1.31).

latitude x d.b.h. x elevational class (table 13). Lowest ratios were found in latitudes 45 degrees through 50 degrees, at medium elevation, in trees 152 mm in d.b.h. Maximum ratios were found at 60 degrees latitude. Also trees 228 mm in d.b.h. at latitudes 52.5 degrees and north had high ratios, as did 76-mm trees at low elevation at 40 degrees latitude (table 13). That is, the lowest ratios were at midlatitudinal range, medium elevation, and mid-diameter range, whereas maximum values were at the extremes of latitude, elevational classes, and d.b.h.

Identification of Trees That Will Have Low r_1/r_2 Ratios—In addition to the significant interaction: latitude x d.b.h. x elevational class, the tree-average r_1/r_2 ratio was significantly (0.05 level) correlated with a few tree characteristics, as follows:

Sign of correlation and tree characteristic	*r*
Positive	
Age at 152-mm-high stump top	0.312
Stem taper within live crown, millimeters per meter	.252
Maximum stem crook, inches	.185
Latitude, degrees	.148
Total number of cones on first foot of top 25 branches	.131
Negative	
Average ring width at 152-mm-high stump top	−0.241
Number of live branches	−.181
Average live branch angle	−.158
Length of live crown	−.155
Crown ratio	−.132

These data suggest that low r_1/r_2 ratios will be found in fast-growing young trees with little stem taper in live crowns, little stem crook, few cones on topmost branches, many live branches, long crowns, and large crown ratios.

Variation of Ratio r_1/r_2 Within *Latifolia* Trees—The ratio r_1r_2 varied significantly with height in *latifolia* trees, the relationship differing with d.b.h. class (fig. 32). When this ratio of each of the 2,430 (243 trees x 10 heights) *latifolia* sections was correlated—and each of the 360 *murrayana* sections similarly correlated—with each section's other properties, some significant relationships were evident as follows:

Section's characteristic correlated with the section's r_1/r_2 ratio	*Latifolia* (n = 2,430) *r*	*Murrayana* (n = 360) *r*
Positive		
e/r_1	0.851	0.884
e	.623	.779
Percentage compression wood (fig. 19)	.378	.518
Wood specific gravity	.197	.312
Major diameter	.120	.189
Negative		
Out-of-roundness index (fig. 25)	−0.274	−0.283
Height above ground, meters	−.168	−.325
Wood moisture content	−.148	−.302

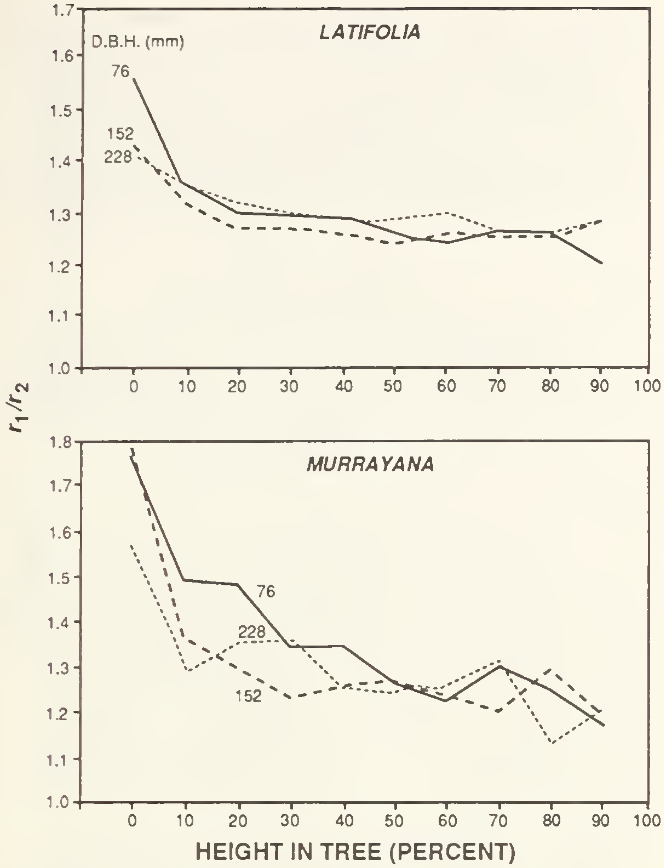


Figure 32—Variation of the ratio r_1/r_2 with height in stems of *latifolia* (81 of each d.b.h.) and *murrayana* (12 of each d.b.h.) trees of three diameters.

Obviously those sections with low values of e and e/r_1 will have low ratios of r_1/r_2. Additionally, small ratios will tend to be found in short logs of small diameter and circular section taken high above ground with little compression wood (fig. 19), low specific gravity, and high moisture content.

Murrayana—r_1/r_2

Variety *murrayana* had tree-average r_1/r_2 ratio of 1.32 with standard deviation of 0.16 and range from 1.12 to 1.64. Values did not differ significantly with latitude or diameter class; there was no significant latitude x diameter interaction. Averages by diameter are summarized as follows:

D.b.h.	*n*	Mean
mm		
76	12	1.36
152	12	1.31
228	12	1.29

With data for all three diameters pooled, tree-average values by latitude were as follows:

Latitude	*n*	Mean
Degrees		
37.5	9	1.35
40	9	1.37
42.5	9	1.33
45	9	1.23

The ratio r_1/r_2 varied significantly with percent height in *murrayana* trees, the relationship differing with d.b.h. class (fig. 32). As noted under the discussion of *latifolia* trees (and tabulation of correlation coefficients), stem sections or short logs sampled from *murrayana* trees will tend to have low ratios of r_1/r_2 if they are of small diameter with circular section, and have little compression wood (fig. 19), low specific gravity, and high moisture content—and are taken high above ground.

r_1/r_2 of *Latifolia* Compared to *Murrayana*

Tree-average ratio r_1/r_2 did not differ significantly between *murrayana* and *latifolia*; see table 6 for comparative values. For varietal differences among individual sections see figures 19, 25, and 32.

CONCLUSIONS

Compression Wood Content

- Compression wood is extremely difficult to detect visually in log ends under woods or mill conditions.

- Stems of virtually all lodgepole pine trees have some compression wood. Of the 243 *latifolia* trees analyzed, only one was free of compression wood. None of the 36 *murrayana* trees examined were free of compression wood. Trees 76 mm in d.b.h. of both varieties had significantly higher stem-average percentage of compression wood than those 152 mm or 228 mm in d.b.h. *Latifolia* trees had less stemwood compression-wood content (5.5 percent) than *murrayana* trees (7.7 percent).

- When evaluating entire stems, highest proportions of compression wood will be found in slow-growing, small-diameter (for example, 76 mm), short trees with little heartwood at stump height, large live-branch angle (branches near horizontal), high stemwood specific gravity, and a relatively high proportion of complete-tree weight represented by the stump-root system and by cones. Lowest stem-average proportions of compression wood will be found in fast-growing, tall trees with long crowns comprised of many branches with small branch angle (and a relatively high proportion of complete-tree weight represented by branches), high sapwood moisture content, much heartwood at stump height, thick stump bark, and a low proportion of complete-tree weight represented by the stump-root system. Stemwood in such trees will have a lower specific gravity than stemwood of trees with a high proportion of compression wood.

• In both *latifolia* and *murrayana* only about one-third of all sections taken at tenth points of tree height have little or no compression wood. Trees 76 mm in d.b.h. had a smaller percentage of sections with little or no compression wood than trees 152 mm or 228 mm in d.b.h. In both varieties, sections sampled at 45 degrees through 50 degrees of latitude had the greatest proportion of sections free of compression wood.

• Of the sections that do have compression wood, nearly three-quarters will display a typical compression-wood pattern (fig. 8, pattern #1) of one-sided eccentricity in which the main body of compression wood is opposite an eccentrically located pith, and along a line projected from pith through the center of the largest circle that can be inscribed within the section (fig. 9B).

• In both *latifolia* and *murrayana* incidence of compression-wood pattern #1 dominates near ground level (fig. 14), but incidence of this pattern diminishes with height in tree. Sections free of compression wood are infrequent in the lower stem; upper stem sections are more frequently free of compression wood.

• Sections or short logs sampled from stems of both varieties will tend to have high percentages of compression wood if they are out of round and close to ground level, and have eccentric piths, high specific gravities, and low moisture contents (figs. 19, 20, and 21). Also, there is a weak tendency for small-diameter wood to have more percentage compression wood than large-diameter wood.

• One of the better indicators of compression-wood content in stem sections or short logs (fig. 19) is the ratio e/r_1 (defined in fig. 9). This ratio will be smallest (and compression wood content low) if sections are cylindrical with centered piths; small ratios will also tend to be found in high-above-ground sections of large diameter, low specific gravity, and high moisture content.

• The ratio r_1/r_2 (defined in fig. 9) is also one of the better indicators of compression wood content (fig. 19).

Stemwood Out-of-Roundness

• Tree-average out-of-roundness index (fig. 9) averages 0.91 and does not differ significantly between varieties or with tree d.b.h. or elevational zone. It does vary with latitude, however; tree stems are most nearly circular in average cross section in those latitudinal zones from 40 degrees to 55 degrees (with the exception of zones at 47.5 degrees and 52.5 degrees), and are more elliptical in the northernmost zones of 57.5 and 60 degrees.

• In addition to latitudinal differences, entire stems are most likely to average most circular in cross section in fast-growing trees of high moisture content, low specific gravity, with pith not eccentric, little stem crook, low bark percentage of complete-tree ovendry weight, and with many small branches making a small angle with the stem above them. Because latitude is inversely correlated with the elevation at which *latifolia* grows, trees at higher elevations may have stems more nearly circular in cross section than those at lowest elevation.

• Stemwood of both varieties is most nearly circular in cross section near midheight (fig. 24).

• Sections or short logs of stemwood of both varieties will tend to be out of round if they contain much compression wood, have eccentric piths, high specific gravity, small minor diameter, and low moisture content; the last two relationships, although statistically significant, are weak.

Minor Stemwood Diameter

• In trees of comparable d.b.h. (within the range of this study), and at comparable percentages of tree height, *murrayana* stems have slightly smaller minor diameters (defined in fig. 9A) than *latifolia* stems (fig. 27).

Pith Eccentricity, *e*

• Tree-average pith eccentricity, *e* (defined in fig. 9), averages about 6.7 mm and does not differ between varieties. Small-diameter trees have significantly less pith eccentricity than large trees (fig. 28), and trees average least eccentricity if growing in the midelevational zone. Pith eccentricity in *latifolia* is smallest (5.5-6.3 mm) in the intermediate latitudinal zone from 45 to 52.5 degrees, and is larger in more southerly and more northerly latitudes (6.8-8.0 mm).

• Tree-average pith eccentricity is least in slow-growing, small-diameter, short trees with circular stem sections, and heartwood and stembark of high moisture content—but sapwood of low moisture content.

• Individual sections or short logs will have least pith eccentricity if they are small in diameter, near circular in cross section, and in the upper stem (figs. 28 and 29), and if they have little compression wood, low specific gravity, and high moisture content (figs. 29 and 30).

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Trees 76 mm d.b.h. had higher stem-average percentage of compression wood than those 152 mm or 228 mm d.b.h. *Latifolia* had less compression wood (5.5 percent) than *murrayana* (7.7 percent). In both varieties, stem sections from 45° through 50° latitude were proportionally more free of compression wood than sections from other latitudes. Transverse stem sections typically displayed a main body of compression wood opposite an eccentrically located pith. Percentage of compression wood tended to be higher in stems that were out of round and close to ground level, and if pith was eccentric, specific gravity high, and moisture content low. Cross sections averaged most elliptical in trees from 57.5° and 60° latitude. Both varieties were most nearly circular in cross section near midheight. Pith eccentricity averaged 6.7 mm and was least in intermediate latitudes (45° through 52.5°).

KEYWORDS: wood technology, forest products, pith eccentricity, stem form, geographic variation, *Pinus contorta* var. *latifolia*, *Pinus contorta* var. *murrayana*

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